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"Study of Pre-Shaped Membrane Mirrors and Electrostatic Mirrors with Nonlinear-Optical Correction"

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13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking Research Institute for Laser Physics as follows: The aim of this work is to improve low- weight membrane mirror characteristics intended for relaying laser communication beams in space. Such systems would use a non-linear-optical corrector to correct surface figure and other optical aberrations. The analytical part of this project is aimed at estimating the feasibility of designing the mirrors based on the pre-shaped membranes. This evaluation will give a clear understanding of the approaches to forming super-light mirrors as well as of the problems anticipated in creating this new generation of space mirrors. In the course of the experimental work, a low- weight mirror model based on the pre-shaped membrane will be fabricated, and its optical characteristics will be studied. It is expected that the characteristics predicted theoretically will be observed experimentally.

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Large telescopes and super light mirrors
Overview

Nowadays a number of scientific and practical fields of activity need solutions of the problems requiring high- resolution of both ground and space based telescopes with substantial space penetrating power, namely ones with large aperture mirrors.

First of all, these high- resolution physical instruments are required for astronomic observations. For example, the National Research Council of the National Academy of Sciences of the USA states the strategic tasks of astronomic observations as follows: "We must use the universe as a laboratory - a unique laboratory - for probing the laws of physics in regimes not accessible on Earth, such as the very early universe or near the event horizon of a black hole." "We must search for life beyond the Earth and, if it is found, determine its nature and its distribution. And finally, we must develop a conceptual framework that accounts for all that we have observed," the report says [1]. Note that at present the requirements to a telescope for some tasks [2] are the resolution of the order of 10^{-3} arcsec and space penetrating power of stars of the 35th- 38th magnitude. This means that a primary mirror must be of the order of 100m in diameter.

Obviously, high- resolution telescopes will be useful for space monitoring the Earth as well as for observations directed to struggle against terrorist organizations.

Large dimension optics is of interest for usage in concentrators of solar energy, laser- beam forming systems, commutation systems, lidars et al.. Certainly, fabrication of high-precision primaries and other optics are not required for all the systems. The requires to precision are most rigorous in the case of observing objects with diffraction limited resolution in visible and infrared light. The surface errors of primary mirrors in this case must not be more than a small fraction of the wavelength used.

By now a number of investigations have been carried out, which show that in high –precision telescopes with the system of correction of optical distortions it is possible to employ a primary mirror of non-ideal optical quality. Therefore, this overview will concern not only the systems with high-quality primaries but also the systems with light primary mirrors of low optical quality.

Telescopic systems are classified as the ground –based and space-based ones. Currently a number of telescopes with primary mirrors more than 5m in diameter are successfully operating on the Earth. An example of a high –precision large –dimension space telescope is Hubble telescope having its primary of diameter of 2.4m.

Space telescopes have a number of advantages as compared to ground –based ones. First of all it is due to full exclusion of harmful atmospheric effects on image quality. However, recently partial atmospheric-turbulence compensation has become possible due to employment of active optics used for correction of wave- front distortions. One of the first works in this field is that R.Q. Fugate with colleagues performed with the use of a natural or an artificial laser- guiding star [3]. Even for the

best possible wave front correction, residual atmospheric aberrations result in a halo of scattered light that will prevent detection of earth-like extra solar planets [4].

In addition, while atmospheric absorption actually blocks observation at most wavelengths longer two microns [4], the space telescopes have an advantage as compared to ground-based ones in that they can observe in the whole spectrum of electro-magnetic irradiation. Along with this, to deal with insignificant absorption is especially important for observation of remote objects with great red shift in the IR light. These observations are most interesting for studying the Universe Origin.

Another advantage of space telescopes with passive cooling (temperature of the order of 50K) is absence of ground radiation in the middle IR where the ground telescopes strongly radiate.

Absence of a weight effect in space allows in principle using the telescopes of greater dimension as compared to ground systems.

In late 90th the USA listed some prestigious projects of astronomic instruments for 2000- 2010 [1]. The first in this list was the Next Generation Space Telescope (NGST) having deployable in space 8m-mirror. The telescope's orbit is to be distant from the Earth at $1.5 \cdot 10^6$ km, and the launch is planned in 2007- 2009. Its assumed cost is 1billion dollars. The second listed is the ground telescope with its mirror of diameter of 30m. Its name is Giant Segmented Mirror Telescope (GSMT). There is also another name for it, CELT. The assumed cost of this telescope is 350 million dollars.

Ground telescopes of 8- 10 m class and future projects (up to 100m)

For a long time the American telescope, **Hale** with its mirror's diameter of 5 m built in 1950 and the Russian Large Astronomic telescope with its diameter of 6m (1976) were considered to be the tops of traditional telescope design. To design telescopes with mirrors of greater dimension it appeared necessary to develop new technologies that allow transferring to the mirrors of more light constructions and in future to flexible mirrors. An approach to the construction of primaries has also changed: the segmented mirrors instead of monolithic ones are considered in the majority of projects.

During two last decades the telescopes of a new generation with diameter of their primaries of the order of 8- 10 m were built. The ground telescopes with the largest monolithic mirrors (D=8.2m) are four telescopes ((UT-I – UT-IV) of the system Very Large Telescope (VLT). They were commissioned in 1998- 2000 and now are successfully operating in the Europe South Observatory (ESO). They cover the spectral range of 420- 10050 nm. Their thin flexible mirrors have been manufactured of glass-like material Zerodur with very low coefficient of linear expansion. They have a more light cellular construction and active control of their surface shape. Note that the mirror 8.2m in diameter of the telescope UT weights 23.5 tons whereas the monolithic primary mirror of diameter of 6m in the Russian Large Astronomical Telescope (？？？) weights 42 tons.

The authors of [5] consider the potentialities of designing with the use of monolithic primary mirror to be virtually exhausted for diameters of the order of 8 m. An alternative for monolithic mirrors are segmented ones. Segmentation allows reducing mirror's weight that is an essential step forward in designing of ground as well as space telescopes.

As advantages of segmented primaries can be considered the following:

- transportation of the mirror from the place of fabrication to the working place is simplified;
- processing of a rather small segment does not exhibit a problem like that in processing of a large dimension mirror;
- segmented mirrors are tolerant to increasing their diameter by means of attaching additional segments.

However, this architecture of the mirror is not yet free of a number of disadvantages associated in essential with great mobility of its elements.

At the present time the ground telescopes with segmented primary mirrors largest in diameter (D=10 m) are the two telescopes Keck I and Keck II (see, for example, [2,6-8]), commissioned in 1991 and 1996, respectively, and successfully operating at Hawaii. These are first large telescopes with segmented primary mirrors. Each of the primary mirrors comprises 36 aspheric hexagonal segments with 0.9-m long edge and has its active control. Their spectral range of observations lies within 0.3-27 µm, resolution amounts to 0.5arcsec, and the limit star magnitude is m=27. The telescopes show very good quality [6]. They have been built at California Technology Institute.

Now some words about the projects of ground telescopes.

Starting in 90th , a large number of groups and firms in various countries in the world are working in development of the projects of ground telescopes with segmented primary mirrors 25 - 100 m in diameter. The authors of the projects of ground super-telescopes consider development of them to be expedient because they can help to solve fundamental astronomic problems. This can reduce urgent necessity of building new space telescopes and decrease expenses as compared to those needed for their building. Thus, the developers could concentrate at the tasks, which cannot be undertaken from ground because of physical rather then technological reasons [9].

Here we give briefly characteristics of these two projects.

CELT (California Extremely Large Telescope):

The primary segmented mirror 30 m in diameter is to consist of 1080 hexagonal aspheric segments with their edges 0.5 m long. The mirror is to have actuators (3420 pieces) with the limit displacement of 1 mm. An error of a segment position must be controlled to accuracy of 10 nm. The telescope can operate in the regime with a limited quality of seeing in the spectral range of 0.3- 30 µm at the field of view of 20 arcsec. With the use of adaptive optics (AO) it is planned to obtain an image of diffraction quality at a wavelength up to 1µm over the field of view of 1´-2´. They assume to use an adaptive optics and various guiding laser sources and expect to build the telescope in 2010 -2015. There exist a number of unsolved problems in this project. A number of investigations are necessary to carry out. There are no needed technologies yet in particular for adaptive optics. At the same time, the basic things concerning feasibility of such a telescope are not doubted [7]. The assumed cost of the project is 0.3 billion dollars.

OWL (Over Whelmingly Large):

Primary mirror's diameter is to be 100 m. The spherical primary and flat secondary mirrors are both segmented ones. In the case of the primary mirror made of traditional materials such as Zerodur or fused quartz it will weight 1500- 1700 tons (areal density of 190- 216 kg/m2). However, usage of such a material as silicon carbide can reduce the areal density down to 50- 80 kg/m2. The system is assumed to involve a 4-elements corrector of spherical and field aberrations (two active monolithic mirrors of the 8-m class, the 4-m passive and 2.5-m flat mirrors).

The telescope concept involves achievements acquired when designing 8-m-10-m –class telescopes. The main of them are as follows:
1) experience in segmentation basing on the telescopes Keck;
2) optical and mechanical solutions employed in the telescope Hobby-Eberly being effective in cost (primary mirror of diameter of 9.2 m) [6];
3) active optical control (VLT et al.).

The requirements to OWL are: the diffraction limited image quality in the field of view of 30´´ for the visible light and over the field of view of 2´ (for ?~2µm).

They assume to employ an adaptive correction of atmospheric turbulence and not obtain quality of seeing worse than 0.5´´. A natural and an artificial laser-guiding star will be used in the system.

The assumed cost of this Europe project is to amount to1billion Euro (including the cost of the primary mirror of 266.7 million Euro, the cost of the rest optics of 80.3 million Euro, the cost of adaptive optics of 47 million Euro, the cost of mechanics of 229 million Euro, the cost of control systems of 17 million Euro etc) [9].

Space telescopes and their projects

Nowadays the only large telescope operating in space is Hubble telescope (HST) having its primary mirror of diameter of 2.4m. The HST was inserted into the near-earth orbit (distance of 600 km from the Earth) in 1990. It is planned to be in the space at least till 2005. On evidence from data in [10] the resolution of the telescope is of the order of $6^.10$-2 arcsec and from the data reported in another paper [8] -$7^.10$-3 arcsec. The telescope operates in the spectral range 0.1- 2.5 µm, the limit star magnitude m=30 [8]. On evidence derived from various publications the areal density of the primary mirror varies from 185 kg/m2 [11] to 345 kg/m2 [10]. It is agreed [12] that the HST is one of the most successful and important endeavors undertaken in the twentieth century.

Nowadays the large optical systems flying in the space are mainly the systems of the non-imaging class characterized by low requirements to the quality of their optics. These are, for example, inflatable concentrators of solar energy [13], antennas for communication. Their diameters are of the order of 30 -40 m and surface errors of the order of centimeters [14]. There are known also the flying projectors LAMP [15], lidars [16]. The program of the Large Deployable Reflector (LDR) has been developed [17]. The LDR mirror is to have its diameter of 20 m with surface errors (rms) of the order of tens µm. The system is intended for operation in far IR.

In 1997 the radio-telescope with its primary mirror 8m in diameter (HALKA) was launched in an orbit [18]. Note that no deployed primary mirrors have been yet used for optical/IR space telescopes [14].

There currently exist a great number of projects of space telescopes. As was mentioned above the most important of them is the project NGST. Note that almost all large space projects are treated as telescopes allowing observation images and spectra mainly in IR light from the wavelengths 0.8µm -5µm (near IR) to 40µm -500µm (far IR). This is related to that the objects characterized by great red displacement and most interesting for cosmology are largely studied in the near IR area. Half the luminosity of the universe and 48% of the photons released since the Big Band is now

observable at far IR wavelengths (40-500 µm) and the Earth's atmosphere prevents sensitive observation from the ground. Thus it is one of the last unexplored frontiers of space astronomy [19].

We give here some data concerning the project NGST which is the main space project of NASA in the first decade of 21st century [1]. It is especially interesting for that it is developed on the basis of the newest achievements in the technology of designing modern large ground and space telescopes. The NGST is to be built in cooperation of NASA and national space agencies of Europe (ESA) and Canada (CSA). The NGST scientific program is sufficiently like the programs of ground telescopes. It involves cosmology tasks, problems of the origin and evolution of galaxies and origin and formation of stars and others. However, a large-dimension space telescope can essentially broaden these programs. Our knowledge of the history of the universe is well constrained at very early ($t_{univ} < 300000$ yrs) and very late ($t_{univ} > 5*10^9$ yrs) theses in its evolution [20]. To probe the universe as it was between few million $< t_{univ} <$ few billion years requires a new type of observatory. Such an observatory must be capable of collecting the very faint signal of objects (first stars and galaxies are very faint sources, their luminosity amounts to1-3 nanoyanski (1 yanski=10-26 W/m2/Hz)). It must have high resolution to separate the images of objects from the background. The NGST is to be such an observatory. To operate in the near IR light (1µm -5µm) and even at ?>5µm the telescope's temperature must be less than 60K.

The NGST is sufficiently light deployable in space telescope, which is to be inserted into point L2 of the Earth-Sun orbit. Its developers believe that beyond the earth atmosphere the NGST will enjoy access to all wavelengths from 1-30 µm and should be fully diffraction-limited at all wavelengths longer 2 µm over a field-of-view $4'*4'$ [21].

The NGST will be passively cooled to less than 50K, and thus see extraordinarily low background emission from the near-infrared, where ground-based observations are hindered by OH airglow, to the mid-infrared, where ground-based telescopes themselves radiate strongly. Thus for imaging and spectroscopy, particularly in surveys at wavelengths beyond 2µm, the NGST have an enormous sensitivity advantage over large ground-based telescopes.

Development of the architectures of the NGST must be implemented taking into account the following reasons [22]:

To develop a new rocket for launching the telescope is not economical. Thus, its payload must be limited by several tons in weight. The primary mirror is too large to fit inside an available launch shroud. So, it must be made from segments folded up and stored for launch, then deployed and aligned in space. On board wavefront sensors will measure phase errors to correct them with actuators.

The folded up mirrors must be less than 4-5m in diameter, and the primary mirror must weight less than 800 kg. Thus, the areal density of the whole mirror must be less than 15 kg/m2. The NGST as a whole must comprise the following basic units [23]:
1) Optical Telescope Assembly (OTA)
2) Integrated Science Instrument Module (ISIM)
3) Solar screen and Spacecraft Support Module (SSM)

The NGST is to be launched by rockets Atlas V-531 [22] or Atlas IIAS [20]. Designing the NGST will involve development of technologies of OTA, ultra-light cryogenic mirrors, cryogenic actuators, a cryogenic deformable mirror, deployable structures, systems of controlling wavefronts

and some other [24]. As the basic concept is accepted Yardstick concept which is developed by NASA GSFC (Goddard Space Flight Center) ? STSI (Space Telescope Science Institute) [25].

The primary mirror in this concept on version of [25] consists of the central segment 3.3 m in diameter enclosed by eight lobes those to be deployed after orbiting the mirror. The total weight of the telescope must be less than 3300 kg. On the version reported in [26] the Yardstick architecture has only 7 lobes, all of them are extended hexagonal ones. The central lobe is 2.5 m in dimension and the side extended lobes measure 2.2m x 1.8m. The primary mirror is characterized by f/D=1.25.

The architecture Yardstick creates a real image of the input pupil in the plane of the deformable mirror (DM) that implements precise correction of residual distortions of the primary mirror including the distortions caused by gravity and thermal gradients [25]. Then a Fast Steering Mirror (FSM) implements fast pointing and stabilization of the direction. These mirrors enable correction of various disturbances on the orbit. We should say that nowadays the clear understanding of a future architecture of the NGST does not exist. It is not yet decided the number and shape of its segments, and the material of the primary mirror.

Thus, for example, though Yardick's architecture is based on hexagonal segments the architecture developed by Thomson Ramo Wooldridge Inc./Ball Aerospace and Technologies Corp. (TWR/Ball) [27] considers the version of keystone-shape segments. Every large segment can in turn comprise pieces of a smaller size.

Before the NGST will be built, various firms are carrying out wide investigations concerning both the structure of the primary mirror and choice of materials for its fabrication. They consider mirror's behavior in cryogenic and no gravity environments. They decide problems associated with deploying telescope's elements on the orbit as well as with alignment and control of the optics.

Development of the mirrors for the NGST is carried out in the programs NMSD (NGST Mirror System Demonstrator) [15, 24, 28], AMSD (Advanced Mirror System Demonstrator) [24,29], SBMD (Subscale Beryllium Mirror Demonstrator) [20] and some other. The mirror up to 2 m in diameter with areal density less than 15 kg/m2 (12- 13 kg.m2) [15] and diffraction limited quality has been fabricated for a demonstration. The proposed architecture of the NGST involves a deployable both the primary and the secondary mirrors. At first light, following deployment, optical aberrations are expected to be large. Alignment shifts during launch, deployment errors, thermal deformation, mirror fabrication errors and other effects can combine to cause initial wavefront errors to several millimeters [30]. The whole process splits into distinct stages including:
1) initial target capture, segment mirror course alignment and focusing, which bring the wavefront errors down to sub-millimeter.
2) course phasing using dispersed fringe sensor (DFS) and white light interferometry (WLI), which bring the wavefront errors down from sub-millimeter to sub-micron; and
3) fine phasing using the phase retrieval to bring the wavefront errors further down for few nanometers range [31].

To test the adjustment procedure for a telescope in ground conditions a special test bed DCATT (Developmental Cryogenic Active Telescope Testbed [20], or in [32] – Developmental Comparative Active Telescope Testbed [31, 32]) has been built.

Completing section 2, we conclude that the largest diameters of primaries in modern projects of space telescopes are approximately of 25 m (N-NGST) [33] and 35 m [34].

Super-light mirrors

The needs of science and engineering in the large aperture telescopes result in necessity to reduce telescope's weight and its primary mirror's areal density. Apertures of diameter of 8 m require employment of segmented mirrors in both ground-based and space telescopes. As for space telescopes the segmentation is necessary in principle because restrictions of modern launching systems by diameter of the payload of 4-5 m [35]. For orbiting the total weight of a space telescope must not exceed several tons [22].

When designing the NGST they assumed that the total weight of the telescope must not exceed 3300 kg [23-25], the total weight of its primary mirror must be less than 800 kg, and its areal density not more than 15 kg/m2. The last is determined by the density of the mirror itself, its support structure, actuators et al.. The mirror's own areal density must be less than 5-7 kg/m2 [36]. Noted that since the time of development of Hubble telescope primary with its areal density of ~250 kg/m2 the DoD (Department of Defense) has developed the mirror with areal density of 35 kg/m2 (1980), and by 2000 the demonstrators for NGST with areal density of the order of 13-15 kg/m2 have been developed.

Development of technologies in the field of designing light mirrors with a small areal density was in great part stimulated by the NGST concept. It was necessary to choose on one hand a proper structure of the mirror and on the other hand proper materials.

Designing of the mirror to operate effectively in normal conditions as well as at a cryogenic temperature is a sufficiently complicated task. The matter is that the mirror surface must have its precise shape and curvature at a large drop of temperature. This requires good material characteristics including low coefficient of temperature expansion (CTE), high heat conductivity within the range of temperature drops etc.. In the programs (NMSD, AMSD) of development of the mirror for the NGST [15, 24, 37-40] there were mainly considered two concepts of the mirror's structure.
   1) semi-rigid hybrid mirror developed by COI (Composite Optics Incorporation)
   2) flexible membrane mirror with a great number of actuators (University Arizona).

The structural, thermal and optical properties of the both types of the mirror were investigated in [37].

   1) As an example of a semi-rigid hybrid mirror for the demonstrator can be a circular mirror 1.6 m in diameter described in [20]. It consists of a 3.2 mm thick face plate (of Zerodur) attached to a light composite core of graphite/epoxy material 7.6 cm in thickness and a back plate of the same material [20, 37]. The hybrid mirror is attached with flexures and actuators to a light composite support structure of carbon fiber epoxy [38]. The own areal density of the mirror is approximately 7.4 kg/m2 [37].
   2) The membrane mirror in [15, 28] with a great number of actuators has hexagonal shape 2 m in dimension. Its face plate made of borate-silicate glass 2 mm in thickness. The plate is attached to actuators (~150- 200 pieces) placing on a support structure of carbon fiber/cyanate ester [15]. The areal density of the mirror as a whole amounts to~13 kg/m2, and the mirror's own areal density is 4.4 kg/m2 [15].

The mirrors of the first and second types have their advantages and disadvantages.

The thin meniscus facesheet generally has many actuators ($\sim$ 50 act/m^2, [41]), providing very high authority surface control. As a result, the thin-meniscus design approach is very robust to thermal-induced errors, material mismatch, residual mount strains, actuator failures and other parameters. Note that while treating a thin-meniscus, one must attach it to a blocking body [38]. The disadvantage to this design approach is the large number of parts, data processing and electronics associated with driving the actuators.

The main advantage of the semi-rigid mirror consists in less complexity of its construction.

Now some words on actuators.

While there has been a great deal of actuator development over the last decade to support ground-based deformable mirror systems, there has been little development in space-qualified lightweight actuators for primary mirror applications. The AMSD requirements have forced designers to develop actuators that have a large dynamic range, very small resolution, wide bandwidths, and low masses. In addition to these challenging requirements, the actuators must also be space flight qualifiable, able to operate at ambient and cryogenic temperatures, and have roughly a 10-year life in which they may be cycled several times per second over that lifetime. The stressing requirements placed on the actuators, the large percentage of AMSD areal density allocated to the actuators, and the relative immaturity of actuator technology for space-based applications has put the actuators on the critical path for AMSD success [38].

Now we consider the problem of materials required for the mirror. A typical mirror system design requires materials for the surface cladding, facesheet, core, back plate, and reaction structure. In additional optical –mechanical materials are also required, but we will not discuss them here.

Material specifications should define the chemical composition, grain size and distribution, phases present, size, shape, morphology and distribution, elastic properties, thermal strain, density, thermal expansion, thermal conductivity, and specific heat. The AMSD program is developing mirror system designs employing materials that are expected to operate at both an ambient temperature, 300 $\pm$ 10 Kelvin, and cryogenic temperature, 35 + 20/-5 Kelvin [38].

Table 1

Mirror Faceplate	Core	Cladding	Reaction Structure
Quarts	Carbon Fiber/Epoxy	Electroless Ni	Carbon-Fiber Epoxy
ULE	Composite	Silicon	Composite
Zerodur	Be	SiC (Chemically Vapor Deposited)	Be
Be	C/SiC		
C/SiC	Zerodur		
Si/SiC	ULE^{TM}		
Borosilicate Glass	Si/SiC		
	Fused Quartz		

Table 1 [38] exhibits the data on materials, possible candidates for the mirror AMSD, those to be worth of considering. The material being considered are those that are available in necessary size

and were used in the desired temperature ranges. The cryogenic properties of many of these materials have not been rigorously measured or specified.

The materials in table 1 are categorized into 5 different classes – 1) glass, 2) metals and alloys, 3) non-metals, 4) ceramic and composite structures, 5) composite structures of carbon fiber/epoxy [38].

1) Glass. Its properties are well known. Glass is sufficiently stable in time and at a changing temperature. Glasses have a comparatively low coefficient of temperature expansion (CTE) and Young's modulus. The main advantage of glass is its availability in large dimensions.

2) Metals and alloys. Be is one of metals having the best rigidity to weight ratio. In the temperature range 75-100K, CTE of Be is close to 0, but is large at the room temperature. At the right processing (spherical powder) Be can be isotropic. It is possible to obtain monolithic structures of Be up to 2 m in diameter [38]. In [20] the mirror of diameter of 53 cm was described which the face and back surfaces were fabricated of spherically powdered Be, the faceplate being 2.5 mm thick. The areal density of the mirror amounted to 1.2 kg/m2.

3) Non-metals and non-metal alloys. A proper material for mirrors as well as for cladding is Si. They used it for fabrication of mirrors of very good surface shape. It is possible to grow single crystals up to 6 cm in size, and the crystals of smaller diameter have been grown as long as 2.75 m. Si can be used as a cladding for a two-phase substance so that to polish surfaces to the required accuracy. The cladding is typically applied with high-temperature chemical vaporization (CVD). An essential disadvantage of Si as a single crystal is its anisotropy.

4) Ceramics and composite substances. First materials of this class considered as candidates for AMSD were SiC and alloys of Si/SiC. Thermal strains of these materials in the temperature range 300 -35 K are intermediate between Be and glasses with low CTE. SiC shows large specific rigidity (E/ρ), an alloy with Si has it lower. Alloys Si/SiC can also be used as cladding though they spoil at cryogenic temperatures. Hybrid mirrors can be fabricated with the use of foamy Si or SiC covered by various materials. The materials of this class have been developed much worse than glasses [20, 40, 42].

5) Graphite-epoxy composites. These materials have low density and elasticity module like that of glasses. It is possible to fabricate light elements of them, thus they are ideal material for fabrication of very light and rigid structures.

The programs AMSD and NMSD developing the mirrors used different approaches, and depending on the chosen material and other peculiarities of the mirror its areal density could vary. As was said above the areal density of the mirror fabricated of borosilicate glass 2 mm in thickness amounted to 4.4 kg/m2. With this, the total weight of the 8-m mirror could be 623 kg (taking into account actuators, electronic devices, cables, support structure and other elements) [15]. In the future, the areal density is to be a twofold decrease in magnitude with the use of the 1 mm thick plate. In this case the mirror's weight will be 250 kg. It was reported in [43] that a great number of 1-3 kg/m2 areal -density reflectors existed capable to operate in microwave and millimeter wave spectral ranges.

The technique of building super-light mirrors capable to fold up like cylinder and return to their original shape in the deployed state was considered for optical applications in [11, 35]. The material for fabrication of such a mirror must have a good memory of shape. There was fabricated the mirror 0.9 m in diameter comprising layers of epoxy gum with carbon fiber of the type M55I/EX-1515. The areal density of the mirror amounted to 2- 5 kg/m2, surface errors RMS being

approximately of 0.05? (λ=632.8 nm). The technique of replication was used for fabrication of those mirrors.

In summary, we can say that the existing technology of development of light mirrors for the 10-m telescopes (NGST type) can enable the required areal density. However, to build space telescopes of the tens-meter diameter class with the mirrors having a precise surface shape for optical applications one needs to decrease areal density more and more down to values of the order of 1 kg/m2 and even to 0.1 kg/m2.

The further line of the development technology for tens -meter mirrors is apparently that one basing on thin-film materials. The film membrane optics has potentiality for weight reduction and aperture increase an order of magnitude of the mirrors for super- light space- based optical systems.

Decrease of the density of film mirrors is possible due to usage of very thin films. Thus, the minimal thickness of film mirrors can reach tens or even units µm whereas this parameter for mirrors of non-film materials amounts to several hundreds µm [45]. Taking into account that the volume density of films (~1.4 g/cm3 for nylon [14]) is close to that of non-film materials (~2 g/cm3), one using a film mirror can have the 10-100 fold gain in areal density. This density for a 20-µm-polyimide –film mirror can amount to ~0.03 kg/m2. A thin film or membrane mirror is potentially easier storable, deployable, reproducible, and cheaper as compared to glass or metal optics. When designing large thin-film mirrors the main problem is the very poor optical quality of film membranes. The role of active optics then would be to adjust for very large figure errors. Although the requirements are beyond the present range of active correctors, this limitation might be overcome with advances in technology. Another difficulty with membranes is related to fine-scale roughness [10]. The scale is too fine to be corrected by active optics, so the challenge is to manufacture smoother membranes.

Typically, the film surface is plane. To have a concave mirror's surface, in particular of a large curvature, one has to use some special measures.

Maximal dimensions of the existing films are of the order of several tens meters (10 m [44]). To increase diameter it is possible to build a segmented film mirror. However, it is problematic because there is a useless aperture zone near the membrane perimeter [44].

The required shape of the thin-film mirror having been deployed in space must be fixed, then rigidized with the use of a number techniques [44], for example, with inflating [46-55], electrostatic forces (see, for instance, [4]) or with epoxy gum [44].

The line of development of large thin-film space mirrors is sufficiently elaborated for the cases of not high precision of specular surfaces [8, 13, 14]. Several of current designs for the NGST use large deployable sunshields 15-20 m in dimension and consisting of a 4-6-layer thin film for passive cooling the telescope. The various materials of the type of teflon, mylar, capton and some other are considered [56].

To build space telescopes with the mirrors capable to form images of the diffraction limited quality in the optical spectrum is still the task to be solved. The authors of [57] consider the arising new technologies to have potentiality of improvement to develop precise thin-film mirrors for space applications.

A great cycle of investigations of film mirrors for space telescopes has been performed at AFRL (Air Force Research Laboratory), USA, starting in late 80th [46-52, 55]. In the experiments, the inflatable film mirror was designed as follows. They mounted a polyimide membrane 275 mm in diameter with its thickness varying from 20µm to 200 µm on an external optically plane annular construction and then stretched it on an internal ring being also plane. They had the both rings covered by Al or Ni. Thus they made a cavity in the system which they could either pump out or inflate so that the originally plane membrane could acquire various curvatures due to changing its tension and gas pressure. The surface of the inflated curved membrane was neither spherical nor parabolic (oblate spheroid). Its basic error is referred to as w-profile error [47, 53]. The more was the previous tension of the membrane the closer to a sphere its surface became [46].

In [50] to approximate the shape of the membrane surface to near- parabolic they proposed along with previous tension to employ a plunger capable to shift the central area of the membrane along its optical axis. The preliminary results obtained have shown a feasibility of the surface shape close to parabolic over a substantial area of the aperture.

The requirements to the membrane minimal tension were considered in [52]. They proposed to make the tension so that to eliminate large-scale errors and the small-scale errors caused by local variations of the membrane thickness to fit the bandwidth of an adaptive system. They also took into account possibility of employment of the correction system based on real-time holography techniques (RTH).

Trying to approximate the surface shape of an inflatable membrane mirror to parabolic, Breckinridge with co-authors (IPL – Iet Propulsion Lab.) came to employing mylar films with their thickness varying in a parabola along radial direction. They described the technique of designing such a mirror in [54].

Employment of inflatable mirrors shows a number of difficulties because these systems require an additional transparent film shell having good optical quality (of lens-like shape). In the inflatable systems, the correction of mirror's local errors is impossible without application of special techniques. There exists also a danger from meteorites.

In addition to investigations of inflatable film mirrors, the researchers from AFRL proposed in [51] a novel version of a membrane telescope. A thin membrane 10-100µm in thickness is to be packed and then deployed on orbit without inflating. Instead of inflatable lens-like construction they concentrated on the close-to-accurate film's shape reproduced with the cladding enabled the correcting tension.

The authors of [53] proposed instead of an inflatable mirror to use a flexible but non-elastic very thin membrane rolled in a cigar-like cylinder for launch.

It is rather important is the problem of a correction technique for film mirrors.
Distributed actuators on the primary mirror provide a means of adjusting the local mirror shape, a feature that inflating cannot provide by itself. The methods based on a direct contact affect only a small area of the mirror surface with small-bending stiffness, and thus without an unacceptably large number of actuators can implement only very little correction.

When using non-contact affecting it is possible to apply various methods, such as electric field causing effect of electrostatic forces, piezoeffect, electrostriction and magnetostriction. We mention

only techniques with the use of electrostatics for changing a surface shape and correction of its errors (see, for example, [4, 22, 44, 59-61]).

There are a great number of literature sources with descriptions of designs and applications of electrostatic actuators to implement changing a mirror surface shape and correction of wave-front errors. Thus, as applied to the concept of a large dimension telescope with its primary consisting of plane segments the authors of [4] proposed to give the segments a concave shape by application of a proper electrical potential between the membrane and electrodes located behind it (SMEC - Stretched Membrane with Electrostatic Curvature).

Under the action of electrical forces the silicon nitride membrane 15 mm in diameter and 0.6µm in thickness covered by the 0.1µm thick layer of Al acquired the concave shape 6 m in curvature at the voltage of 133 V. The authors considered also possibility of employment of the concept SMEC in the telescope with a 10µm thick polyimide membrane mirror 4 m in diameter. The authors believe that with the membrane stretched on a light frame they can achieve areal density of 1-2 kg/m2. Then the total density of the mirror with actuators and fastenings will amount to~3.5 kg/m2. In [59] a system of micro-actuators governed by electrostatics has been described. The system of the electrodes had a structure of concentric rings. The electrodes were placed at the bottom of the wafer of silicone. Above the wafer at the distance of 4µm gap was located the 0.2 µm thick silicone membrane mirror covered by Al. The radius of the mirror amounted to 500µm. Being deformed it acquired the parabolic shape having the shift 0.8µm in magnitude at the center.

As it is noted in [61] a previous symmetric tension and uniform pressure on a circular membrane allow one to approximate its shape to a paraboloid of rotation. However, a finite fluidity limit of membrane material does not allow one to obtain in this way the mirror characterized by a small numeric aperture ($N_F=F/D$). The solution of the problem lies apparently in the way of employment of the membrane having a required previous shape. It was shown in [62] that under certain forces of both tension and uniform pressure applied to the parabolic membrane surface the membrane extended proportionally still being an 'ideal' paraboloid.

We mention one more work [63] containing a discussion of one more method of governing the mirror surface. The mirror for space telescopes in the system described is a reflecting polymer piezoelectric film. An electron flow released by an electron gun controls the film shape and its curvature. The authors have fabricated such a mirror of rectangular form measured 5 cm×10 cm. They could change the mirror's shape with sensitivity of the order of 150 nm, the range of changes reaching millimeters. The authors consider the proposed technology to allow fabricating of a telescope mirror close to 30 m in diameter. The areal density of such mirrors can reach 1 kg/m2.

As is known, one of the promising potentials of correction of primary –mirror- surface distortions is application of dynamic holography techniques (RTH – Real-Time Holography). This line of development is widely researched last years (see, for example, [8, 52, 55, 64-72]).

Current DM (Deformable Mirror) technology is typically capable of removing a few waves of optical path deviation at refresh rates of several hundred Hz and is useful in applications, such as atmospheric turbulence compensation, where the aberration's magnitude and dynamic behavior lie within this correction range. For the case of very severe aberration greatly exceeding10 wavelengths and for fast dynamic compensation the conventional DM systems are currently not adequate.

In [66] with the use of SLM (Optically Addressed Space Light Modulator) there was demonstrated RTH correction of super large distortions 200 wavelengths in magnitude of a thin membrane mirror (4 mm thick) 15 cm in diameter and 120 cm in radius of curvature. The diffraction efficiency of the hologram was 40% with the time response of 600µsec. The density of hologram strokes amounted to 30 mm-1. The coefficient of the image correction was more than $200^?$.

The authors of [70] employed a photorefractive crystal for compensation for distortions of the thin film mirror 150 mm in diameter, 29µm in thickness and 3000 mm in curvature radius. The distortions of the mirror were so large that the dimension of a focused image exceeded the diffraction limit approximately 100 times. However in the case of employment of a corrector-hologram they obtained only 3-5-fold exceeding.

In [55] they corrected with the use of RTH the errors of a membrane mirror of larger dimension (D=280 ? ?).

The authors of [67] compensated for the distortions tens wavelengths in magnitude of a mirror surface by means of OASLM. The mirror had its diameter of 0.75 m and curvature radius of 6 m. The distortions were caused by thermal and mechanical fluctuations and air turbulence. The working frequency bandwidth amounted up to 5 kHz. Correction implemented for objects observed in both monochromatic (λ=532 nm) and non-monochromatic (λ=532±40 nm) light.

The authors of [8, 72] have proposed the version of a space telescope with correction of aberrations of its primary mirror with the RTH technique. They believe such a telescope to be launched approximately in 2007 (the time of launching NGST) having in mind that its primary mirror will be of much more dimensions and the cost substantially lower as compared to that of the NGST primary. The laser source required for this space system is to locate at a long distance from the telescope.

As applied to the problem of development of a large space telescope the considered RTH correction techniques have their own difficulties.

One important area where DM$^/$s typically provide superior performance is spectral bandwidth. The RTH correction is wavelength dependent and leads to residual phase errors when the wavelength of the image light deviates from the wavelength recording the hologram. While novel concepts have been proposed to extend the correctable bandwidth [68,69] and demonstration have indicated a high degree of correction over 50 to 300 nm [66] extended optical bandwidths, this affect can ultimately limit the correctable spectral bandwidth.

Another drawback of the method of dynamic holography correction is the typical requirement of high resolution of the hologram (~2000 lines/mm [8]) and the requirement of diffraction efficiency close to 100%.

In closing the review, we note the main tasks assumed to solve during execution of this contract:
1. Development and fabrication by means of a galvanic plastic technique of a thin metallic mirror up to 150 mm in diameter and 1-0.3 mm in thickness. The surface of the mirror must enable the image quality close to that of diffraction limited in visible light

2. Development of the technique of electrostatic actuating of a film mirror up to 200 mm in diameter and up to 20µm in thickness. In principle, actuating must enable the required shape of the mirror surface.

For the both types of the mirror, the feasibility of the required shape of the surface and correction of errors are to be verified with the use of proper adjustments and actuating.

During the research work the necessary theoretical calculations will be executed. We consider the chosen development lines to be sufficiently perspective for development of super-light mirrors in application to large telescopes.

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1   INTRODUCTION

The problems in designing of large-scale high-quality mirrors are that to persuade the specialists to develop techniques of both linear and non-linear correction of optical distortions. The reason is that fabrication of these mirrors and maintenance of their high optical quality in exploitation present an extremely complex task.

Employment of one or another of the systems for correction of distortions in an optical system, in turn, allows one to think of usage of large-aperture membrane mirrors, which are, on the one hand, of poor optical quality, and on the other hand, look tempting for their low weight and compactness for transportation. Currently a large number of researches are aimed at designing mirrors having their areas density (weight per unit area) less than 10 kg/m2. The said above shows actuality of investigations aimed at improvement of optical quality of the large-aperture membrane mirrors.

To develop a plane-membrane mirror one must do the two primary things: fabricate the membrane having equal thickness over the entire membrane surface, and fasten it on a plane mounting. The variations of straining forces as well as the mounting shape in the membrane plane are inessential. This is not the case for development of focusing membrane mirrors. To design such a mirror one must assure along with uniform thickness of the membrane and its plane mounting the following

- a high accuracy of the mounting shape;
- uniform straining;
- matching of the straining forces center with the mounting center;
- high uniformity of the membrane physical-technical parameters over the entire mirror's area etc.;

This report presents the results of the theoretical studies aimed at improvement of the membrane-mirror characteristics. Here, we are mainly dealing with the optical quality of such a mirror and the problems in designing focusing mirrors with small F-number (=f/D, where f is the focal length, and D diameter of the clear aperture of the mirror).

2   Formulation of the task

Before going to the essence of our studies and the results obtained, we define more exactly the task formulation. Nowadays it is of interest of researchers to design a low-weight large-aperture focusing mirror with its focal length approximately as long as mirror's diameter. A priory it is accepted to be impossible to design such a mirror of ideal optical quality.

However, deviation of the mirror-surface shape from the required one, for example, a parabolic or spherical one must not be more than that allowed by present-day correction systems. Since the allowed defects and their dynamics in mirror's optical quality are determined by the

employed correction system, both the mirror and the correction system must be developed in parallel with mutual co-ordination of their parameters. However, basing on our experimental experience we are sure that the present-day correction systems can operate successively with the mirrors reflecting a quasi-plane incident beam into the beam having 80% of energy within the cone with its vertex angle of hundreds diffraction limits. Without going into details, we accept this as the allowed non-ideality of a membrane-mirror surface.

The distortions of the surface shape may be classified into two groups of physical and technical nature.

1) As physical reasons for deviations of the membrane-mirror surface from the required ideal shape, we consider those conditioned by physical phenomena resulting in deformations of the surface profile though all elements in the mirror construction are precisely fabricated.

2) the "technical" reasons become apparent as deviations of the surface shape of a real mirror from that of the mirror with ideal elements. They can be primarily caused by the following factors:

a) errors (both static and dynamic) in membrane fixation and inaccuracy in the forces applied;

b) non-ideality of membrane material properties (variation of thickness, non-isotropic elastic features etc.)

The theoretical description of such a mirror may involve researcher's mistakes or errors of caused by

a) an unequal mathematical model;

b) non-ideality of calculation algorithms.

During the research process, we made our efforts to minimize researcher's mistakes with the use of analytic studies (giving clear indications of their application scope) as well as of various program packages for computation.

3   Focusing plane - film mirror

The simplest version of an elastic focusing mirror is the mirror formed of an initially plane circular membrane subjected to uniform lateral pressure and uniform straining of the film edge. The mathematical model of such a mirror is presented in [1, 2]. The shape of a surface section of this mirror is described by the sum of a parabola and the polynomial characterizing a deviation of the mirror shape from the required one (optical distortion).

The deviation a thin-film mirror shape from the ideal (spherical or parabolic) one amounts to tens wavelengths, and therefore the reflected-beam energy distribution in the focal plane is of a 'geometric' nature [3] (namely, determined by the local angles of beam deflections caused by optical distortions).

The optical quality of an axially symmetric mirror can be characterized by the 'divergence' angle j:

$$j = \max\left[\frac{d}{dr}\left(w(r) - v_p(r)\right)\right] \tag{0.1}$$

where w(r) is the shape of the surface section and $v_p(r)$ of the reference parabolic mirror; r is the radial coordinate.

As it was shown in [2] the circle of angle dimension j in the focal plane includes approximately 90% of total energy. Remember that this portion of energy reflected by the ideal circular mirror is contained within the diffraction-limited angle $j_D = 3.68\ \lambda/2a$, where l is the wavelength of the light, and ? – radius of the mirror.

It should be noted that the starting equations in [1, 2] describe the plane-film behavior at small (in relation to diameter) flexures. Considering the large-relative-aperture mirrors (large deflection), one must take into account changing the mirror's shape accompanying the film deformation. Thus, there the analytic expressions below being of an approximate nature, so getting more accurate results requires numerical simulation of film deformations. For this, we used here the Finite Element Method code COSMOS/M.

3.1 Mirror of plane film without pre-straining

1. It follows from expressions in [2] that the minimal F-number (f/D) for the mirror of thin film without pre-straining (without initial straining of the film) is read as

$$\frac{f}{2a} = \frac{1}{8}\sqrt{\frac{b_1^3 E}{s_b}} \tag{0.2}$$

Where s_b and $?$ is the yield strength and Young module of the film material, respectively,
$b_1 = 1.35 \div 1.39$ is the number depending only on Poisson's ratio, u.
The typical values for mylar are: $s_b = 0.5$ MPa , $? = 450$ MPa ; $u = 0.3$; $b_1 = 1.352$. The minimal F – number for this material is equal to 1.3.
For the mirror formed from a plane film subjected to uniform pressure the 'divergence' angle of a reflected beam is read as [2]:

$$j = \left(\frac{qa}{2Eh}\right)^{\frac{1}{3}} \frac{1}{b_1^4} \tag{0.3}$$

where q is pressure, and h thickness of the film.
The value of angle j can be expressed via F-number as

$$j = \frac{1}{4b_1^3} \frac{a}{f} \approx 0.05 \frac{1}{F - number} \tag{0.4}$$

It is seen from the last expression that the quality of this mirror is extremely bad for any relative-aperture size of interest in practice. As was shown in [1, 2], radial tension of the membrane edge (or application of pre-straining) results in reduction of optical distortions. Pre-straining allows fabricating the mirror of better optical quality but of small curvature for the reason of limitation of applied forces by appearance of plastic deformations in the film. In other words, stresses in the mirror subjected to uniform pressure and tension must not exceed the yield strength (s_b) of the film material.

3.1 Mirror of pre-strained plane film

Pre-straining of the film results in improvement of mirror's shape. The angle j is determined as earlier by (0.1) but coefficient b_1 is the function of a pre-strain:

$$b_1 = \frac{aU_a}{d_0}\left(1 + \frac{d_0^2 d_1}{(aU_a)^3} + O\left((aU_a)^{-6}\right)\right) \tag{0.5}$$

where U_a is the value of radial pre-strain of the film edge;

$$a = \frac{1}{a}\left(\frac{2Eh}{qa}\right)^{\frac{2}{3}}$$

(0.6)

$d_0 = 0.5(1-\upsilon)$; $d_1 = 0.25(3-\upsilon)$.

Strains in the film are the result of actions of pressure and pre-straining. Therefore, the maximum strain at the given pressure is determined by the yield strength to Young module ratio:

$$s = b_1\left(\frac{E}{32}\left(\frac{qa}{h}\right)^2\right)^{\frac{1}{3}}$$

(0.7).

where s is stresses in the film.

In the first approximation for the mirror with pre-strain the following expressions are invariant

$$2Eh\frac{aqa^2}{f}\frac{}{U_a} = inv$$

(0.8)

$$j\left(\frac{U_a}{a}\right)^4\left(\frac{qa}{2Eh}\right)^3 = inv$$

(0.9)
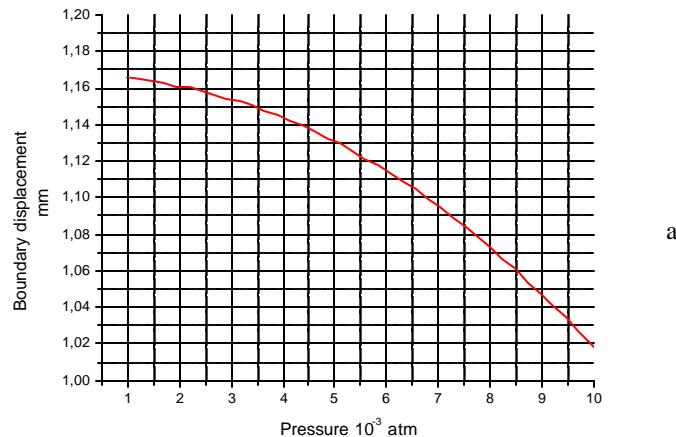
a
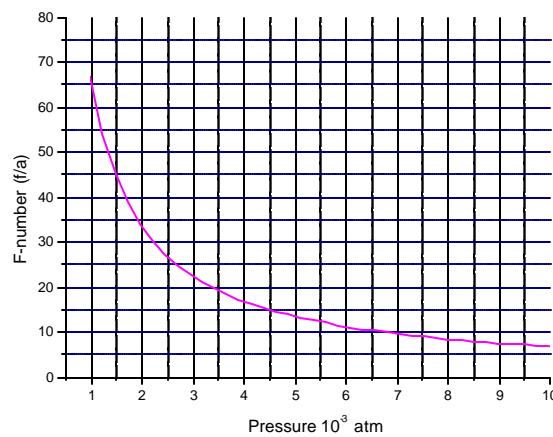
b
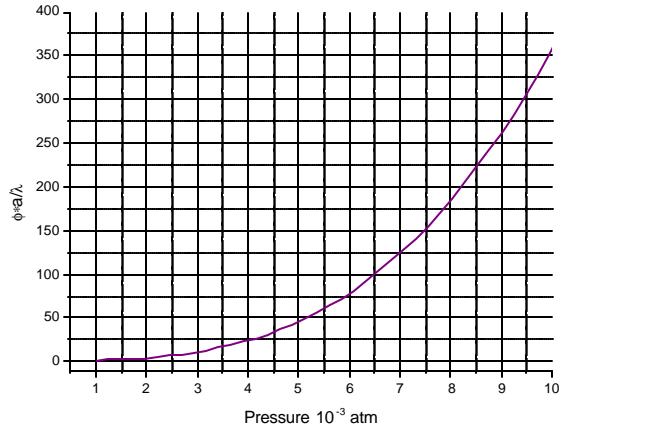
Figure 1
($\mathbf{l} = 1\mu$m – wavelength, **F**-number=f/2a, f-focus, a - radius)

Figure 1 presents maximum possible strain of the film, F-number and the 'divergence' angle as a functions of pressure for the mirror of diameter 2a=300mm fabricated of 20μm thick film characterized by Young's module, 4500MPa, and Poisson's ratio of 0.4. The values of the 'divergence' angle are normalized by the diffraction-limited angle in the visible light ($\mathbf{l} = 1\mu$m).

As it follows from the presented functions, the mirror showing the beam angular divergence equal to 100 diffraction limits in the visible light can have the minimal F-number equal to 10. In the IR light ($\mathbf{l} \approx 10$ μm) the minimal F-number amounts to 4.7.

For comparison consider the mirror of diameter 2b=3m of the same material. As it is seen in (0.8) F-number is constant at simultaneous proportional change of pressure and initial strain up to the values of qa/b and U_ab/a correspondingly. With this, the absolute value of the 'divergence' angle remains (see (0.9)), and the angular 'divergence' measured in diffraction angles changes b/a times.

So, it is impossible to get the focusing mirror 3m in diameter having the acceptable both F-number and optical quality in the visible light with the use of a pre-strained plane film. However, in IR light this mirror is to have its parameters similar those of the mirror 300mm in diameter in the visible light.

It follows from the above expressions that to get large-relative-aperture mirrors with high optical quality fabricated of a pre-strained plane film one has to select the material with a maximal yield strength to Young's module ratio. At the same time, the pre-straining complicates the mirror construction and requires keeping the straining process with high accuracy to get the theoretically predicted quality.

3.2   Mirror of plane film subjected to non-uniform pressure

It follows from the equations for a plane film that a high-optical-quality mirror can be realized by means of radial changing pressure applied to the film. This changing can be implemented, for instance, by electrostatic attraction of the membrane to an auxiliary segmented electrode. Calculation of the auxiliary electrode form and voltage distribution at individual segments one can implement basing on the required value and gradient of force. This calculation seems to be very laborious since it requires simultaneous solution of both electrostatic and mirror's deformation problems.

To illustrate capacity for work of the concept of varying pressure over the mirror surface we consider the quadratic changing of the electrostatic-attraction force. Let the pressure applied to the plane film changes as

$$q = q_0 - q_2 \frac{r^2}{a^2} \tag{0.10}$$

where $\dfrac{q_2}{q_0} = \dfrac{1-u}{2(3-u)}$

Then according to the theory in [4] the film bends so that to form a parabolic mirror with a central deflection read as

$$w_0 = \left(q_0 \frac{4a^4}{hE} \frac{1-u}{3-u} \right)^{\frac{1}{3}} \tag{0.11}$$

The minimal value of F-number of such a mirror is read as

$$\frac{f}{2a} = \frac{1}{8} \sqrt{\frac{3-u}{1-u} \frac{E}{s_b}} \tag{0.12}$$

Substituting here numerical values of the parameters of mylar film we obtain F-number equal to 2.27.

To obtain the pressure in form (0.10) we can combine the electrostatic field between the mirror and the auxiliary electrode (either solid or segmented) with the gas pressure. In spite of additional construction complications related to creation of the electrostatic field, this method shows certain advantages as compared to membrane pre-straining. They are:

- Disuse of the device for pre-straining;
- High theoretically predicted quality;
- Controlling mirror's shape by changing electrode voltage.

4   Pre-shaped mirror

It follows from the preceding section that the solution of the task of designing a thin-film mirror with acceptable optical quality and a small F-number of a plane film encounters a number of principal difficulties. An alternative way to reduce F-number lies in usage of a pre-shaped film. Since a thin film possesses insufficient rigidity to hold a shape it is necessary to apply a pressure to the film and perhaps a tension to the film edge to give the mirror the required rigidity.

4.1   Parabolic pre-shape

A mirror having its pre-shape in the form of a paraboloid of revolution was considered in [4]. The solution of the equations for a membrane with an initial deflection has shown that there is the relation between the applied pressure, the tension of the film edge and the geometric parameters of the paraboloid which enables the mirror to take the paraboloid form similar to the initial one:

$$\frac{U_?}{a} = (1-u) \frac{qf_0}{Eh} \tag{0.13}$$

where f_0 and $?$ is the focal length and the radius of the initial paraboloid, and q, U_a the applied pressure and strain.

Numerical simulation has shown the obtained relations to be valid with a sufficient accuracy for a pre-shape with a small initial deflection. Reduction of F-number results in that according (3.13)

the shape of a mirror's section has large (in wavelength scale) deviations from a parabolic one. These deviations are the larger the more the applied load.

Unfortunately, at present the question remains yet open, whether this deviation is conditioned by the real situation or by a calculation effect. The matter is that with reduction of F-number the surface curvature increases, and the number of computation points required to obtain the results with a given accuracy is growing sharply.

The work in this line continues, and we hope to answer in future the question whether employment of the films with parabolic pre-shapes is possible to design mirrors with a small F-number.

One more way to improve mirror's quality consisted in selection of the pre-shape close to a paraboloid but of a more complex profile. The idea consisted in the following. Pressure was applied to the film with the pre-shape in the form of a paraboloid and the shape of the deformed surface was determined. The difference between the obtained surface and the initial one was subtracted from the paraboloid, and the final surface was taken as the new pre-shape.

This method resulted in decreasing of deviation mirror's form from parabolic one and in improvement of mirror's quality. For mirror with 'corrected' parabolic pre-shape angle φ is shown as a function of r in Figure 2.
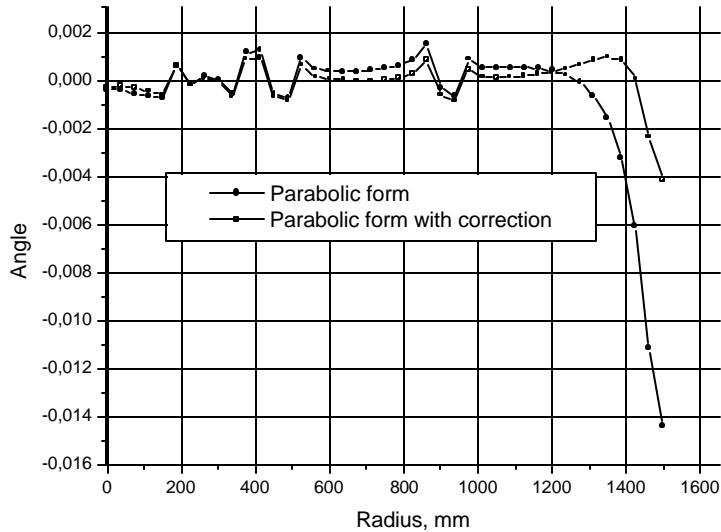

Figure 2

The parameters of the calculated mirror:
Diameter $2a = $ 3000 mm;
Parabolic pre- shape F – number = 0.5
Film thickness h=20μm;
Young's module, E=4500 MPa;
Poisson's ratio, $\upsilon = $ 0.3

The use of the pre-shape correction is resulted in decreasing of 'divergence' angle from 0.016 to 0.005, i.e. in more than three times.

4.2 Spherical pre-shape

Let us consider the membrane having its initial shape in the form of a spherical segment. Applying uniform pressure and proper strain to this film we get the mirror in the form of the large-diameter spherical segment.

$$R_q = R\left(1 + \frac{qR}{2hE}\right)$$

(0.14)

where R ? R_q is curvature radius of the mirror before and after application of the loads, respectively. The value of the corresponding strain of the film is read as

$$U_a = \frac{qaR}{2hE}$$

(0.15)

5 Influence of assembling inaccuracy on mirror profile

5.1 Mirror without pre-shape

5.1.1 Non-coordination between pressure and pre-strain

To get the mirror with the given focal length one must apply pressure and pre-strain related as

$$\frac{a}{f} \approx \sqrt{aa}\,\frac{aU_a}{4d_0}$$

(0.16)

If condition (0.16) is not valid due to inaccurate tensing the film caused by errors of manufacturing (though strain is uniform) or due to inaccurate pressure we get the mirror with its focal length different from the rated one.
.

$$\frac{df}{f} \approx \frac{dq}{q}\,; \qquad \frac{df}{f} \approx \frac{dU_a}{U_a}$$

(0.17)

Here **dq, dU$_a$** is inaccuracy of pressure and pre-strain, respectively, resulting in changing the focal length by the value **df**.

5.1.2 Non-uniform pre-strain

In the preceding sections, we analyzed the elastic-mirror models basing on axial symmetry of the mirror. When assembling the mirror we cannot guarantee the tension of the film to be uniform. To estimate the effect of a non-uniform tension on the mirror shape we carried out numerical simulation with the use of finite element code COSMOS/M. We employed triangular finite elements SHELL3.

Numerical analysis complexity consists in that the mirror dimensions exceed the caused by non-uniform tension deflection of the mirror by several orders of magnitude. Along with this, plane finite elements cause errors in modeling curvilinear surface of the mirror. The value of such an error

is proportional to the element dimension and the surface curvature, and hence increases (at the same number of calculation points) with reduction of F-number of the mirror. Increase of the number of calculation points for the task of strong non-linearity (and hence of slow convergence) results in great spending of time.

The parameters of the considered mirror:
Diameter $2a =$ 3000 mm;
Film thickness h=20µm;
Young's module, E=450kg/mm2;
Poisson's ratio, $\upsilon =$ 0.3
Pressure $q_0 = 0.00065$ atm.

We took the film tension in the form $U(r=a, \boldsymbol{c}) = U_0 + U_1\text{Cos}(n\boldsymbol{c})$, where $U_0 =$ 11.1 ?? is the average strain U_0 , $\boldsymbol{c}$ *the* angular coordinate, and n an even value. The ratio U_1/U_0 determines the magnitude of non-uniformity. n determines the scale of strain variations and related to their linear scale L as $L = \pi a/2n$.
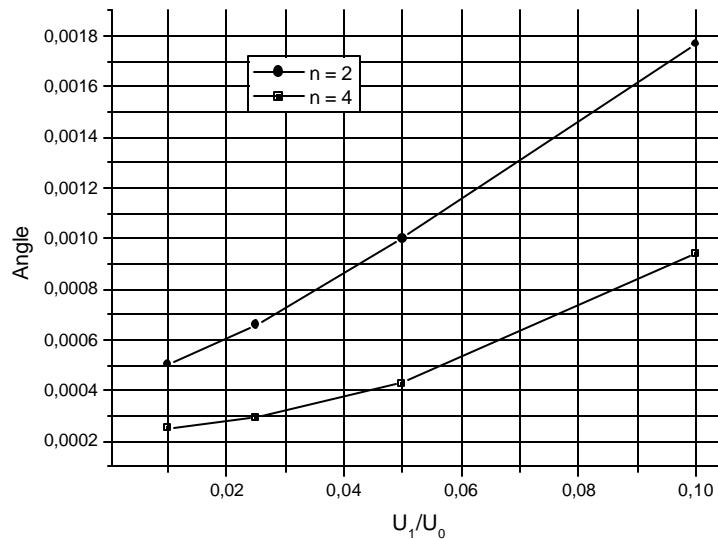
Figure 3

The estimates in section 3.2 allow one to conclude about optical quality of the mirror having other dimensions. In spite of that the estimates have been obtained for the axial symmetry case they are approximately valid also in the case of distortion of the symmetry due to non-uniform tension.

Changing diameter of the mirror for keeping F-number is possible at condition (0.8), namely, at proportional changing the film tension and changing pressure inversely. In this case it is follows from (0.9) that absolute value of a 'divergence' angle remains. However, the 'divergence' measured in diffraction limited angles is growing proportionally with increase of mirror's diameter. This fact with the limited potentiality of distortion correctors gives an additional reason for the segmented construction of telescopes with aberration correction. In such a telescope, the distortion correction performed within each individual sub-aperture must be followed by synchronization of the all sub-apertures.

5.2 Parabolic pre-shape

In this section we present the numerical results for the mirror with the following parameters:
diameter 2a=3000mm;
F-number of the pre-shape =10;
Thickness of the film, h=20µm;
Young module, E=4500MPa;
Poisson's ratio, ?=0.3

5.2.1 Non-coordination between pressure and pre-strain

Equation (0.13) is the condition that enables the film with parabolic pre-shape to gain rigidity and remain its form. However, computation results have shown the mirror shape to deviate from the initial one even at this condition. For the mirror considered at pressure q=0.001atm the 'divergence' angle was approximately equal to 10^{-4}. Change of the strain within 5% did not change the mirror's optical quality.

5.2.2 Non-uniform pre-strain

To find out effect of non-uniform pre-strain we carried out computer simulation of the mirror with a parabolic pre-shape.

The film tension was given as in section 5.1.2, in the form $U(r=a, c) = U_0 + U_1 Cos(nc)$, with $U_0 = 16.45$? ? .

Fig.3 shows dependence of the 'divergence' angle on non-uniform tension at different values of n.
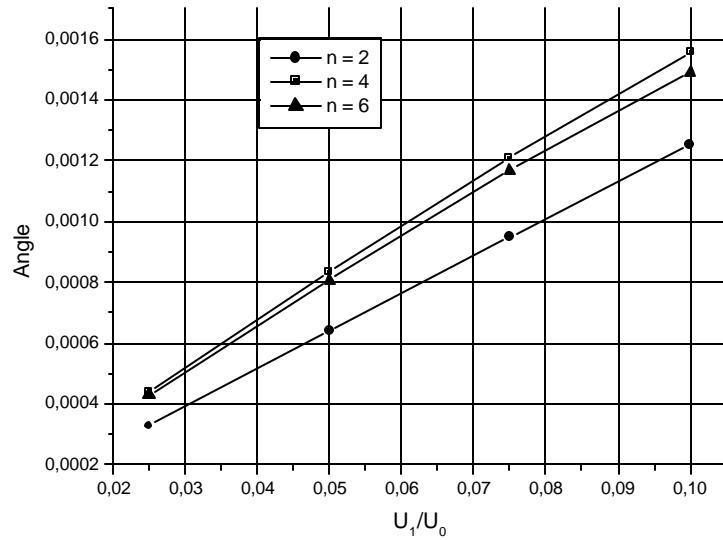

Figure 4

As it follows from condition (3.13), to provide rigidity of the film having a concrete pre-shape one can apply pressure and initial tension in different combinations. However, with increasing the loads the mirror's optical quality deteriorates. At non-uniform pre-strain, the mirror's optical quality depends on both relative non-uniformity and the scale of tension variations. The data

presented show that with decrease of the scale the 'divergence' angle is growing first, then having reached the maximum, is decreasing.

5.3 Distorting of spherical segment at non-coordination of the tension and pressure

If the edge of spherical segment subjected to pressure q is tensioned on the value not equal to one obtained from (0.15), then, in addition to uniform elongation of the radius in accordance with (0.14), extra deformations distorted shape spherical segment will occur. It is known from theory of shells [5] that these deformations are located nearby mirror's edge decreasing with the growth of the distance from the mirror's edge as given by

$$d_x = dU_a * Exp(-bx) \qquad (0.18)$$

where dU_a is a difference between mirror's edge tension and value U_a, defined in accordance with (0.15);
x – distance from the edge;
$$b = \frac{\sqrt[4]{3(1-u^2)}}{\sqrt{Rh}}.$$

The distance at which the extra deformations are not exceeded radiation wavelength is equal to

$$x = \frac{1}{b} \ln\left(\frac{dU_a}{l}\right) \qquad (0.19)$$

Let us consider spherical segment, which parameters are
   diameter 2a=3000mm;
   F-number of the pre-shape =1;
   Radius of the sphere R = 6 m
   Thickness of the film, h=20μm;
   Young module, E=4500MPa;
   Poisson's ratio, ?=0.3

For applied pressure value equal to 0.001 atm, edge displacement must be equal to 10 mm. If deviation of edge displacement from this value is equal to 1% then x = 38 ??. If mirror's edge is not displaced at all, then x = 67 ??. This distance is less then 5% of mirror's clear aperture.

So, almost in the presence at non-coordination of the tension and pressure spherical segment has high optical quality everywhere except edge vicinity.

6 Conclusions

1. The membrane mirrors are tempting for their small areas density (weight per unit area) (<15kg/m2) at a possible large clear aperture. Non-ideal optical quality of the mirror surface forces one to use it in optical systems equipped with a wave-front corrector.

2. Fabrication of a membrane mirror of a plane film is most simple technically. However, to show satisfactory optical quality the membrane has to be {tensioned}. This operation and finiteness of the yield strength of membrane materials prevents from achievement of the required small value of F-number.

3. To reduce F-number and simultaneously improve mirror's optical quality we recommend using films with a pre-shape, for instance, a spherical or parabolic one. To maintain such elastic membranes in their working state one must apply some forces, which, however, can deteriorate mirror's optical quality.

- Parabolic mirror with great F-number (at the condition (1.13));
- Parabolic mirror with small F-number (in this case the membrane must initially have a streamlined parabolic shape with subtraction of expected distortions);
- Spherical mirror with arbitrary F-number (for this the pressure applied to the film and the tensile force must be coordinated).

5. We have performed estimates of sensitivity of the surface shape to some types of technical errors while fabricating mirror's elements. The membrane mirrors fabricated of a plane film and of a pre-shaped film proved to have the same sensitivity to technical errors. However, distortion magnitudes greatly depend on the tensile forces and the applied pressure at the film surface.

6. We assume that distortions of the mirror can be corrected by a pressure variation over the film surface. It is convenient to implement such a variation with electrostatic attraction of the membrane to a segmented electrode. An example of capacity for work of this concept we have shown that the strain force changing as quadratic function reduces distortions of the focusing membrane mirror fabricated of a plane film.

7. Basing on the studies carried out, we think that present-day technologies allow designing concave spherical membrane mirrors of several meters in diameter with required F-number and satisfactory optical quality.

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The third quarterly report for ISTC Registration No 2103p, entitled
"Study of pre-shaped membrane mirrors and electrostatic mirrors with nonlinear-optical correction"

Part 1
Fabrication with galvanic-plastic technology and certification of experimental samples of super-light membrane mirrors with large relative aperture.

1. Introduction

In the framework of this item of the contract, we are studying peculiarities of fabrication with a galvanic-plastic technique of a light mirror 150 mm in diameter designed for feasibility demonstration of a segmented primary mirror of large relative aperture.The galvanic-plastic process is reproduction of accurate metallic replicas by means of electrolytic metal concretion and separation of the precipitated metal from the base die metal. The galvanic-plastic technology allows fabricating complex-shape articles having the given physical-chemical properties. As applied to optical mirrors, the important features of the replicas are roughness and shape of the mirror surface, stability of the shape etc.Micro-roughness and the surface shape of the replicas virtually reproduce roughness and the shape of the die. Mirror's surface quality is determined by polishing (buffing) quality of the die surface. Additional polishing the mirrors-replicas is not required. The thin mirror fabricated with the galvanic-plastic technology does not show sufficient rigidity as traditional monolithic optical mirrors. Therefore, after separation from the die, the mirror's surface of spherical or parabolic shape not always shows its optical quality sufficient for imaging with resolution close to diffraction limited one. However, the errors in the mirror's surface shape one can compensate with one or another correction system. With this, one can obtain diffraction limited imaging on conditions that the mirror's errors do not lie beyond the bonds of the correction system.

The structure of a galvanic-plastic precipitated metal (more often is used nickel) enables stability of parameters of the mirror replica in operation. The galvanic-plastic mirrors exposed to outer forces (for example, gravitational, inertial, thermal loads etc.) in some magnitude range are capable of keeping their shape. Unlike, for instance, glass mirrors, the considered mirrors can withstand pronounced impact loads.

The galvanic-plastic mirror-replicas are reproducible repeatedly with the same die.

Galvanic-plastic mirrors should be classified as light mirrors with reduced mass being less than 15 kg/m2. For example, the reduced mass of the galvanic-plastic mirror in [1] amounted to 13 kg/m2. This paper noted that the reduced **mass** could reach 2 kg/m2.

However, it is worth to note also the drawbacks conditioned by use of nickel in the galvanic-plastic process. These are high specific density of nickel (8-9 kg/dm2) and its high thermal expansion coefficient.

2. Example of realized galvanic -plastic mirror

Figure 1 shows general appearance of a galvanic -plastic mirror with specific mass of 13 kg/m2 fabricated by the authors of [1]. The optical parameters of the mirror was

1. Diameter   355 mm

2. Radius of the convex surface   954.1 mm

3. Surface roughness   <200 nm

4. Thickness of the galvanic-plastic mirror   0.5 mm

5. Mass of the mirror with elements of fastening   1.3 kg

6. Resonant frequency   >400 Hz

7. Thickness of the mirror (including fastening):   50 mm
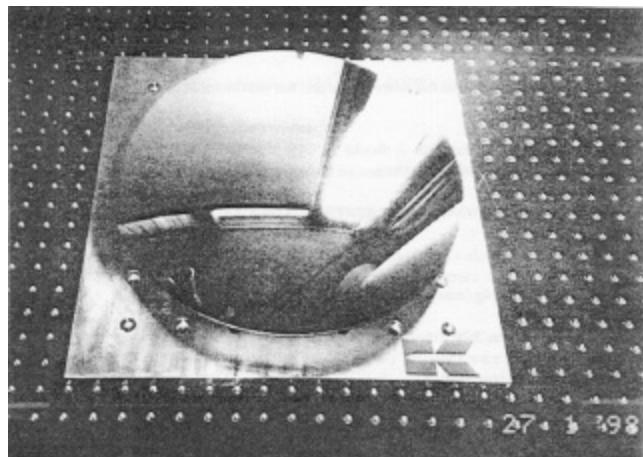
Fig.1 Galvanic-plastic mirror (view from above) [1]

3. Primary phases of mirror fabrication

In the framework of the contract, we are fabricating light mirrors 150 mm in diameter with the use of galvanic-plastic technology. The primary phases of fabrication of the mirror consist in the following:
1. Design and fabrication of the die and additional parts. This phase includes determination of the primary parameters of the mirror, development of both assembly and design drawings of the die and support structure, development of technology, fabrication and control.
We have got the developed package of engineering- technology documents for the mirror die of size of 150 mm (Fig.2 see in the appendix) and now are producing these units.
2. Selection of electrolytes and development of regimes for building up metal
Simultaneously with fabrication of units according to phase 1, we are busied with development of the operation regimes of a galvanic-plastic bath to minimize inner stresses in a nickel mirror-replica. The detail description of the regimes and the obtained preliminary results is given below in section 7.
3. Preparation of the die surface for galvanic-plastic process includes cleaning the surface, degreasing the die etc.

4. Initial building up of metal on the die until entire covering the die surface is referred to as tightening the surface. This phase is distinguishable from the total process of building up nickel of the required thickness by that here nickel precipitates on the metal surface of the die (stainless steel) rather than on the layer of earlier precipitated nickel. Thus, electrolyte structure and electrolyze regimes for the tightening process significantly differ from those in the basic process.

5. The proper process of building up nickel of the required thickness

A peculiarity of this phase is necessity of persistent control of bath operation parameters as well as stability of both the electrolyte and the regimes during all the time of building up the mirror.

6. Control of the structure of the precipitated metal and its mechanical properties, for instance, inner stresses, which must be minimal. To execute this phase of fabrication of the mirror we carry out along with concretion of nickel on the basic mirror its concretion on small technological samples as well. As the mirror grows, these samples are taken out of the bath and we are testing the properties of the precipitated metal. Having got the test results, we can correct the bath parameters.

7. Fastening of elements of the mirror support structure with galvanic-plastic technique. The design makes provision for setting the fabricated thin galvanic mirrors on adjusting mechanisms that belong to the mounting of the segmented primary mirror.

8. Mechanical treatment for removal of technological allowance, outgrowths, excess of metallic nickel on some parts of the tightened die. This operation is executed without separation of the mirror from the die.

9. Thermal treatment of the die with the mirror aimed at reduction of inner stresses in the mirror.

10. Separation of the galvanic-plastic mirror from the die

4. Peculiarities of galvanic process

In view of the fact that fabrication of galvanic –plastic mirrors is feasible with thorough selection of galvanic-bath parameters, we have carried out an analysis of technology peculiarities of this process.

The primary requirements to electrolytes in the galvanic-plastic process are the given physical-chemical and mechanical properties of sediments obtained, high rate of metal concretion, uniform distribution of metal over the cathode surface, electrolyte stability.

At electrolytic metal concretion, even comparatively small changes in electrolyte structure and in the electrolyze regime result in essential changing physical-chemical features.

To intensify the process of building up thick metallic layers the electrolytes in galvanic-plastic procedures are used that allow one conduct electric concretion at high current density, with the use of electrolytes of high metal concentration, with mixing, and the die moving during concretion. Recently for this purpose, one can use different types of current such as reversible one, alternative current applied on continuous one etc.

The issues of electrolyte stability are of great importance in galvanic-plastics. One can obtain good results only with all primary parameters of the electrolyze process being stable. Stability of this process is primarily determined by equilibrium of cathode and anode processes. The metal concretion process lasts for many hours or even days. Thus, significant changes in electrolyte structure can occur due to difference in cathode and anode current. Therefore, it is necessary to control systematically the electrolyte structure and correct it if needed.

When fabricating galvanic-plastic mirrors it is necessary to enable uniform metal distribution over the die surface, and this in turn depends on scattering capability of the electrolyte, mutual positions of cathode and anode, and fashion of current supply of the cathode. It is virtually difficult to find the electrolyte to meet all mentioned requires. So, the electrolyte was chosen taking into account the primary peculiarities of the process.

5. Structure and properties of galvanic-plastic nickel

Nowadays a rather limited number of metals and alloys are used in galvanic-plastics. Most widely are used copper, nickel and iron, and as for alloys nickel-cobalt and nickel-iron. In the course of our analysis of peculiarities of galvanic-plastic process, we have chosen nickel as the mirror material. Electrolytic nickel sediments possess good mechanical characteristics and high corrosion resistance, and increased mechanical durability at temperature below $0^{\circ}?$. These features enable wide application of nickel for electrolytic forming various articles including galvanic-plastic mirrors [6].

The features of nickel sediments depend appreciably on the used electrolyte structure as well as concretion regimes. This is widely used in practice for obtaining units with definite mechanical characteristics. The analysis of literature data shows that the features of electrically precipitated nickel vary in a wide range. For example, the sediments can have rigidity varied from 1.37 to 5.8 GPa, solidity from 0.34 to 1.37 GPa and relative lengthening from 1.5 to 30%.

The structure of sediments obtained from a suthamate electrolyte varies from coarse-grained columnar one at the acidity level of the electrolyte, $??$ 2.5, to small-grained columnar one at pH 5. At higher pH a stratified structure with inner cracks is observed.

Nickel, due to heavily pronounced passivation susceptibility, is sufficiently resistant against atmosphere corrosion. Corrosion resistance of nickel sediments is comparable with corrosion resistance of corrosion-resistant marks of stainless steel.

The rate of oxidation of electrolytic nickel sediments is sufficiently high at an increased temperature (up to $1000^{?}?$) and nearly the same as the oxidation rate of metallurgical nickel, and at a higher temperature the oxidation rate is growing. At $1200^{?}?$ on nickel surface is observed formation of a deep-brown oxide film that is radically decreasing the reflectivity factor of a galvanic-plastic mirror.

6. Inner stresses in galvanic-plastic nickel

One of the main characteristics of nickel sediments is their inner stresses. Great inner stresses cause frequently bursting or partial separation of the sediment from the die during the concretion process as well as variation of geometrical sizes of the article taken off the die (see Table 1).

Table 1
Change of Galvanic-Plastic Mirror's Surface Shape due to Inner Stresses in Nickel

Schematic of forces arising in nickel sediment	Shape of the mirror deformed by stresses

Concave mirror obtained with convex mirror-die		Convex mirror taken off the die	
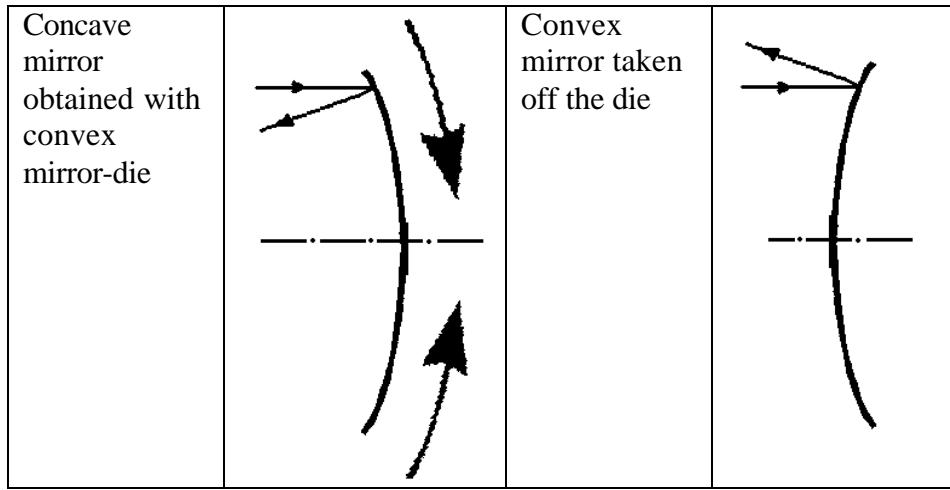
Largely, influence of inner stresses on the shape of the finished mirror takes place in mirrors having small relative aperture and a small deflection and hence their own rigidity. Exactly these mirrors are required for use as segments of a large-scale primary mirror of large relative aperture. Thus, in the framework of this contract we pay attention to investigations aimed at minimizing inner stresses during the electro-technical nickel concretion.

Both and constringent stresses are typical for nickel sediments. The main factors affecting the magnitude and sign of inner stresses are considered below.

1. Type of electrolyte
The value of inner stresses depends on the nature of an electrolyte. Thus, the sediments obtained from a sulphate- electrolyte have high inner stresses whereas the sediments from a sulphamate electrolyte typically have small inner stresses. This enables most wide application of the latter one in galvanic-plastics.

2. Concentration of primary components in electrolyte
The analysis of literature data shows that a sulphamate electrolyte trends to reduction of inner stresses down to zero value with subsequent transition them into constringent stresses. This takes place with changing nickel salt concentration from 100 to 800 g/l, the most considerable variation being in the concentration range of 350-650 g/l.

3. Admixtures (including organic ones)
Admixtures introduced in nickel electrolytes for increasing solidity and luster of sediments change noticeably inner stresses as well. For example, introduction of derivatives of sulfo-aromatic aldehydes into a suphamate electrolyte allows both increasing solidity of nickel sediments up to 6.8 GPa and changing inner stresses from 0.17 GPa to constringent stresses of 0.39 GPa. A whole series of other admixtures are also capable of changing not only the value of inner stress but their sign too.

4. Degree of chemical purity of substances used for preparation of electrolytes
Presence of foreign admixtures (e.g. anions NO^{-2}, $?r?_4^{-2}$ and cations of metals such as chromium, magnesium, cobalt, lead, tin, iron, zinc) leads to noticeable growth of inner stresses.

5. Current density. Inner stresses are found out to increase with increasing cathode current density.

6. Foreign admixtures in an electrolyte that occur during the electrolyze process leads to growth of inner stresses.

7. Acidity level of electrolyte, pH. With changing pH of solutions the inner stress values can pass through their minimum, and with reducing concentration of nickel sulphamate the minimum shifts towards higher values of pH.

8. Temperature of electrolytes. With increasing temperature of electrolytes the inner stresses of sediments are reducing. After concretion in a sulphamate electrolyte at temperature 60 $^?$?, the sediments have insignificant inner stresses. This is caused by enlargement of sediment crystals at a higher temperature.

9. With increasing thickness of sediment the inner stresses are reducing.

For nickel sediments from a sulphate electrolyte the change of inner stresses takes place at thickness up to 10-15 µm. With further increasing of thickness they are virtually keeping constant. In a sulphamate electrolyte the inner stresses are also decreasing with growth of sediment thickness and become constant at thickness more than 20-25µm.

7. Results of development of fabrication regimes

It follows from the data presented concerning the structure and features of galvanic-plastic nickel that manufacturing the mirrors with high optical parameters and small inner stresses requires thorough elaboration of the operation regimes of the galvanic-plastic bath. Now we are conducting this work using the mirror samples 76mm in size and the die having the curvature radius of its convex specular surface of 3.679 m (see Fig.3). The relative aperture of the mirrors amounts to 76:3679~1/50, deflection about 0.2mm. The mirrors have the appearance of a regular hexahedron and are prototypes of mirrors 150mm in size. The galvanic bath parameters obtained during elaboration of operation regimes are to be used when designing mirrors of diameter of 150mm. The parameters of first fabricated samples of size of 76mm and the main regimes are presented in Table 2.
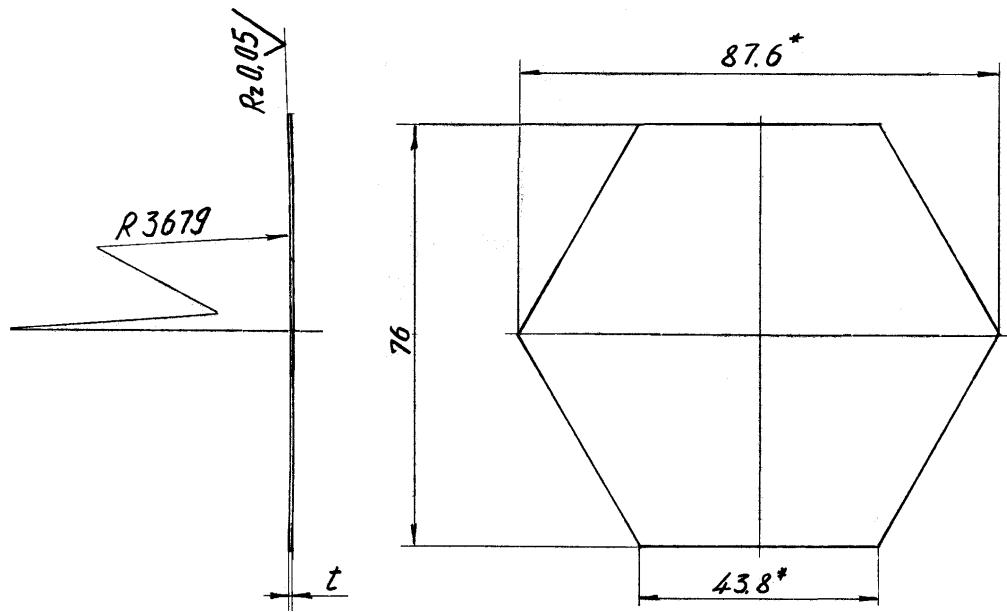

Fig.3 Mirror samples 76mm in size

Table 2

The regimes of fabricating galvanic-plastic-mirror samples 75 mm in size

	6.1.1 Sample number			
	1	2	3	4
Mirror's thickness in its center, t(mm)	0.17	0.45	0.6	0.49
Duration of nickel concretion (hours)	70	160	240	8
Constant current strength (A/m^2)	0.9	0.4	0.25	7.1
6.1.1.1 ?? of sulphamate electrolyte	3.4	3.5	3.6	4.3
Bath volume (l)	40	40	40	75
Temperature of the electrolyte (??)	40	40	40	50
6.1.1.2 Mixing electrolyte	+	+	+	-
Swinging die	+	+	+	-
Rotation of the die	-	-	-	+
6.1.2 Surface quality	6.1.3 Astigmatism			
	Non-reproduced curvature radius of the die Local errors up to 300 diffraction limited angles.			

The data in table 2 are evidence of necessity of further investigations in this line. The work on optimizing parameters of the galvanic-plastic bath is to be continued.

8. Conclusions

In the course of execution of this contract phase, we have carried out studies of galvanic-plastic-technology peculiarities of fabrication of experimental samples for a super-light membrane mirror. We have found out that designing the mirror with high optical quality requires thorough optimizing of galvanic- bath parameters aimed at reduction of inner stresses in the mirror. Taking this into account, we have developed the construction and technology of fabrication for the die of size of 150mm, as well as the supporting structures for the model of a composite primary mirror of size of 750 mm comprising 19 galvanic-plastic segments 150mm in size. Now we are completing production of these units and carrying out elaboration of galvanic-bath regimes.

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Part 2
Preliminary studies of membrane mirror controlled by electric field.

With gas-control of a membrane mirror in space conditions, it is required a "canopy" to keep gas above the mirror's surface. This canopy must have high optical quality to avoid additional distortions of a light beam reflected from the mirror. However, the problem of fabrication such a canopy is equivalent to that of fabrication of the membrane mirror. Solution of this problem is possible with the forces of another physical nature, for instance, magnetic, electrostatic etc. ones affecting the membrane.

Membrane mirror with electrostatic attraction to electrode
Construction of the membrane mirror involves an electrode positioned behind the membrane (Fig.1). Such an electrode can be solid as well as segmented (for example, consisting of concentric rings). Variation of potential distribution in the space between the electrode and the membrane affects the working shape of the mirror surface (Fig.2).
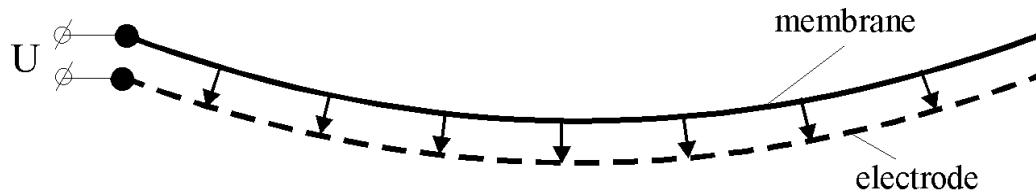
Fig.1Example of membrane mirror with electrostatic attraction of the membrane to a segmented electrode
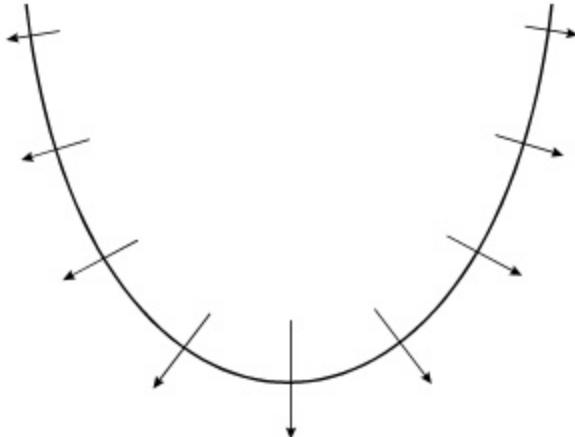
Fig. 2 Action of non-uniform electrostatic forces

In the model experiment, we used a small-scale electrostatic mirror sample (of diameter of 50μm) and studied membrane –mirror curvature versus electric field intensity between the membrane and the electrode. The main experimental results are presented as diagrams in Fig.3.
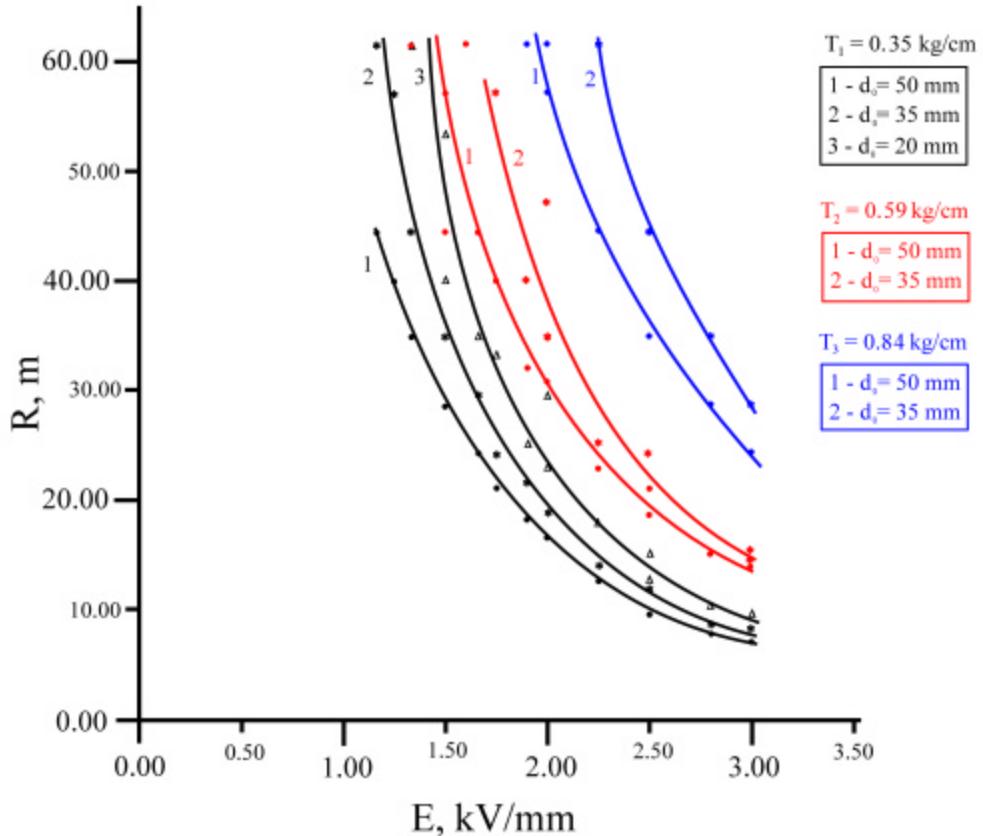
Fig. 3 Curvature radius R of the mirror as function of electric field intensity E for various strains T1-T3 of the film and diameter d0 of the electrode

Analysis of the experimental data results in the following:

1. One can substitute electrostatic attraction for gas pressure

2. Maximum electrostatic pressure realized in experiment at atmosphere pressure amounted to $1.4*10^{-4}$ atm. With this pressure, the curvature radius of the model membrane mirror reached 7m.

3. The maximal electrostatic pressure limited by disruption in the air can be as much as 3 kV/mm.

4. Increasing pre-strain of the membrane leads to increasing the curvature radius of the mirror.

Thus, application of electrostatic attraction force instead of gas pressure does not allow shaping the mirror surface with small F-number. Therefore, to reduce F-number (F/D) and simultaneously improve optical quality of the mirror it is expedient to employ pre-shaped membranes. The pre-shaped membrane can be kept in its working state by comparatively small electrostatic forces. If needed, one can implement controlling the surface shape of the mirror by variation of electrostatic force over membrane surface.

Pre-shaped membrane mirror controlled by electrical force

This concept of fabrication of membrane mirrors consists in the following. A pre-strained thin elastic film (membrane) is applied upon a high-quality die (e.g. lens) that has the required shape. Then after plastic deformation of the film one obtains the membrane with the pre-shaped profile of its surface. The membrane-replica taken off the die is slightly deformed and differs from the die form. With the use of electrostatic field forces, the obtained preliminary surface shape is corrected so to get the required one.

Now, we have carried out a number of investigations in fabrication of membranes with a pre-shaped profile of their surface and formulated a number of basic requirements to the construction of these type mirrors.

Parameters of the developed elastic membrane mirror with its pre-shaped spherical reflecting surface and electrostatic control

1. Clear-aperture diameter up to   200 mm
2. F-number (F/D)   (10 -3)
3. Control voltage   0 – 10 kV
4. Configuration of electrodes:
a) plane electrodes with their solid or segmented surface,
b) spherical electrodes with their solid or segmented surface.
5. Feasibility of various techniques for control of the mirror's surface shape:
a) electrostatic control,
b) control via difference pressure of air,
c) joint electrostatic and difference pressure control.
6. total mass   <5kg.

7 APPENDIX
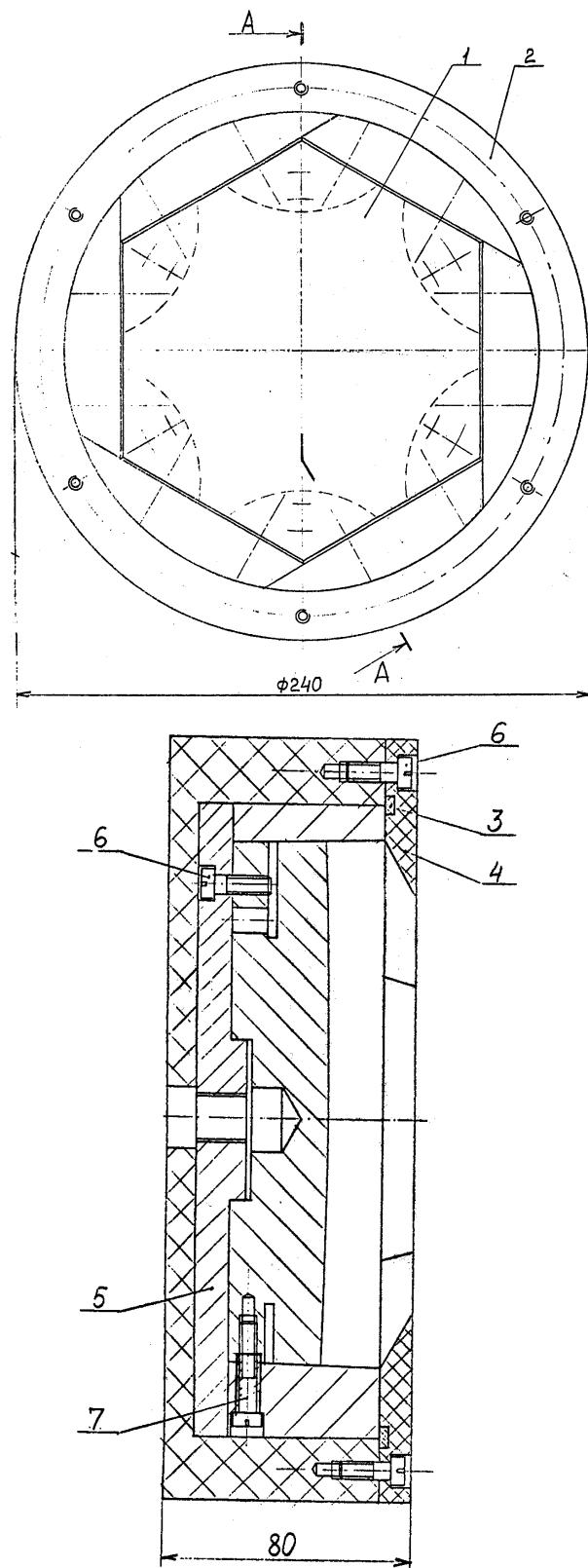
Fig. 2 Die for fabrication of galvanic-plastic mirrors 150 mm in size
1- mirror-die, 2 –mounting, 3- liner, 4- lid, 5 –foundation, 6 –screw, 7- flat mirror.

The fourth quarterly report for ISTC Registration No 2103p, entitled
"Study of pre-shaped membrane mirrors and electrostatic mirrors with nonlinear-optical correction"

1. Introduction

The project 2103p is devoted to feasibility study of light mirrors having non-ideal optical quality but suitable for their use in a telescope with aberration correction of its primary mirror. At the first stage of work under this project, we implemented the review of the literature concerning the problems of designing modern space telescopes. As a conclusion of this review, we noted necessity of further development of works on designing light mirrors being now on the foreground in investigations related to space telescopes for the future. The second part of the work included the theoretical study aimed at designing light membrane mirrors having satisfactory optical quality and acceptable F-number. The third part of the work consisted in analyzing the problems encountered in building up thin metallic mirrors by galvanic plastic method. Below we bring to your notice our report for the fourth stage of work under the project 2103p. In the course of this stage of work, we studied the samples of nickel galvanic plastic mirrors fabricated in the third quarter. We have fabricated the membrane mirror sample with F-number=1.1. The thin membrane was brought to its working state by combination of both forces of gas-pressure difference and electrostatic attraction of the membrane to the electrode located on the rear side of the mirror. We used the electrode comprising several segments. It allowed us to demonstrate the applied to the film force varying over the membrane surface.

We aspired to show an opportunity of creation of varied force since this opens an additional opportunity to control the membrane-mirror's working surface with the purpose to improve its quality. In the course of testing the electrostatic model of the mirror, we have demonstrated feasibility of correction of astigmatism.

2. Fabrication and testing of experimental samples of galvanic-plastic mirror.

Within the framework of the project the samples of light mirrors with the cross size 150 mm have been fabricated by galvanic-plastic method. During the fourth stage of the project, we investigated the parameters of samples of nickel galvanic-plastic mirrors obtained in the third quarter.

Fig. 1 presents the sketch of a mirror, and fig. 2 - the general view of one of the made samples of a galvanic-plastic focusing mirror. The samples look like a regular hexahedron with sides of 87 mm

and diameter of circumcircle of 174 mm. The mirrors have the edges for rigidity around the periphery. Parameters of mirrors are:

1. Clear aperture (incircle's diameter): 150 mm

2. Radius of surface curvature: 3000 mm

3. Surface roughness: <200 nm

4. Mirror's thickness: 0.4 - 0.8 mm

5. Mirror's mass: 80 - 160 g

6. Height of rigidity edges: up to 19 mm
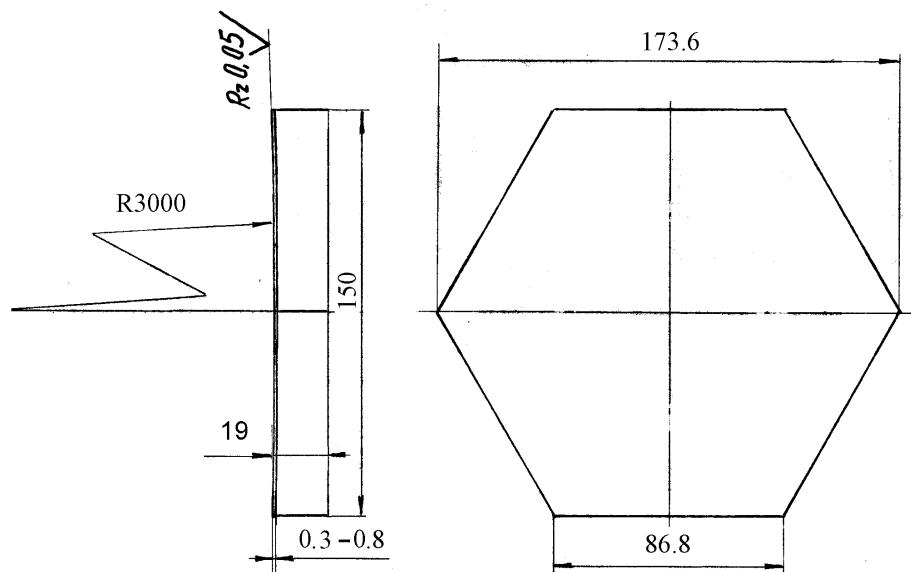
Fig.1. Draft of the mirror sample 150 mm in size (all sizes on the picture are shown in millimeter).
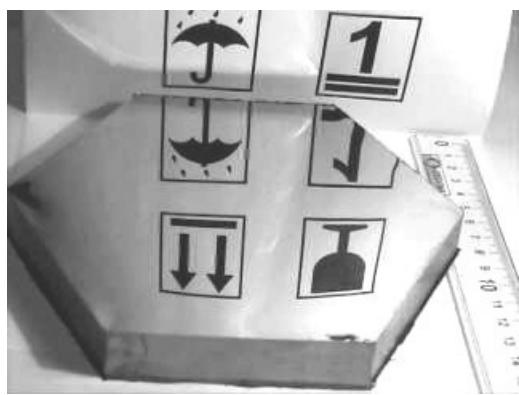
a   b

Fig.2. General view of galvanic-plastic mirror: a – working surface, b – reverse side.

We have described working-out of galvanic-plastic bath regimes for manufacture of mirrors in the report for the third quarter. Now we have fabricated 10 mirror samples, however, the achieved parameters of the mirrors yet do not meet the necessary requirements since optical distortions of mirror's surface shape are very great.

Table 1 exhibits the obtained parameters of galvanic bath's regimes and the parameters of the made samples.

Table 1.

Fabrication regimes and parameters of samples of galvanic-plastic mirrors 150 mm in the size.

7.1.1 Parameter	7.1.2 Sample's Number			
	3	7	8	10
Mirror's thickness in center t (mm)	0.4	0.56	0.71	0.84
Thickness at edge (mm)	0.14	0.32	0.31	0.36
Mirror's mass (g)	83	122	144	158
Time of sedimentation of nickel (hour)	7	14	7	14
Continuous current strength (A/dm^2)	4	3	7.3	5
Bath's volume (l)	80	80	80	80
Temperature of electrolyte ($^?$?)	55	55	55	55
Rotation speed of the matrix (rev/min)	50	50	50	9

When examining optical quality of mirrors we have found out that:

1. Radius of mirror's curvature appears a little bit more than radius of matrix's curvature due to residual inner tensions in nickel,

2. Local mistakes in the mirror's shape are significant and, basically, are determined by non-uniform both thickness and inner tensions over the mirror's surface,

3. The peripheral zone of the mirror about 20 mm in width appears essentially deformed, apparently, because of edge effects in the galvanic bath of the chosen hexahedral mirror's geometry.

The data obtained testify that the further researches aimed at optimization of parameters of galvanic- plastic baths are necessary with the purpose of reduction of inner tensions in nickel. Apparently, it is expedient to pass from the hexahedral mirror's geometry providing best filling the surface for a segmented mirror to the round one showing symmetric edge effects.

3. Fabrication of model of elastic membrane mirror with pre-shaping its working surface.

The previous section is devoted to feasibility of fabrication (by galvanic-plastic method) of a segment of a membrane mirror with a large relative aperture i.e. the mirror with a small F-number. In the framework of the last stage of this contract, we consider the replica method of manufacturing the mirror of a thin mylar membrane as one of possible methods of fabrication these mirrors and the peculiarities of this method.

3.1 Replica method.

The replica process is well known and used for various applications. We decided to use this possibility for fabrication of a membrane mirror which working surface is formed from a thin elastic film that acquires the required pre-profile.

At first sight, pre-shaping does not cause serious complications. We stretch the film on a proper matrix and then fix the obtained form by means of heating it up to the certain temperature. However, there is a number of peculiarities in this application in both the films used for membrane mirrors and the replica process as such.

An elastic thin film having been taken off the matrix cannot have a given spherical or parabolic shape since it does not possess sufficient rigidity. Everybody knows this by the example of child's balloons or balloons for adults flied every fall in Albuquerque. Therefore, to fix a pre-shaped membrane in its working state one needs to apply an additional force to keep the membrane in the required state. For this, we use electrostatic attraction of the film to an electrode positioned behind it as well as pressure difference at both sides of the membrane.

Below we consider the basic stages of fabrication of the elastic membrane mirror with a pre-shaped working surface. We describe the methods of analyzing optical quality of the built mirror and estimate the electrostatic force effect.

3.2 Basic stages and peculiarities of fabrication of pre-shaped membrane mirror model.

To study feasibility of building membrane mirror and then to examine it experimentally we aimed to realize the mirror with about the following parameters:

1. Clear aperture diameter up to……………200mm;
2. F-number (F/D) ………………………...(10 – 3);
3. Control voltage………………………….0 – 10kV;
4. Configuration of electrodes:

   a) plane ones with solid or segmented surface,

   b) spherical ones with solid or segmented surface.

5. Possibility of different choices of mirror's shape control:

   a) electrostatic control,

   b) control by means of air pressure difference at the two membrane's sides,

   c) joint electrostatic and air pressure difference control;

6. Total weight…………………………….< 5kG.

a   b
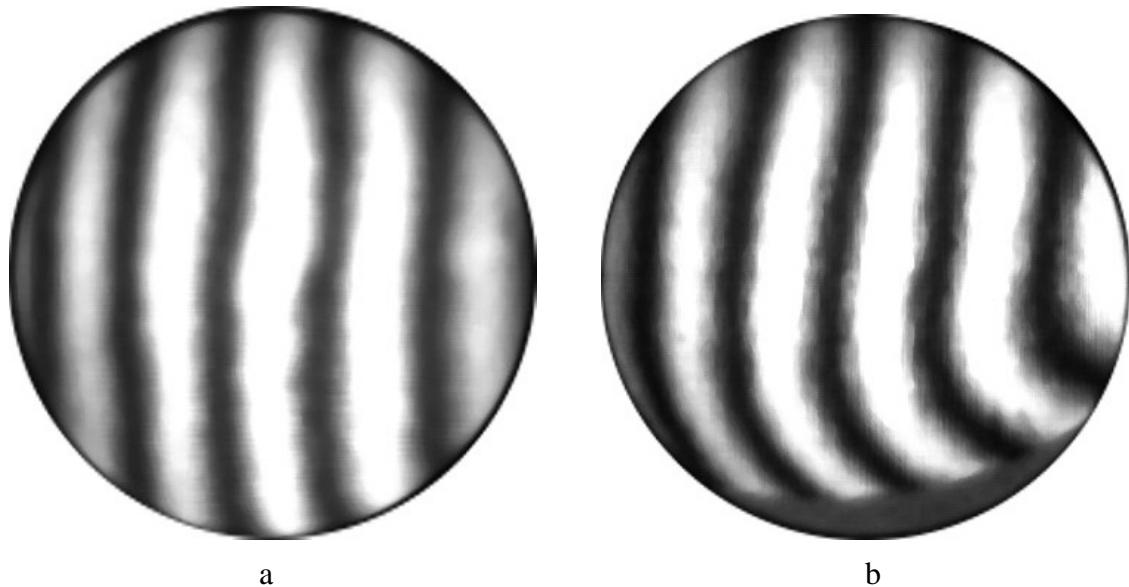
Fig.3. Interferograms of the matrix (a lens) surface at tuning the interferometer for finite-width fringes a) - central area 110 mm in diameter, b) - edge zone.

To make a replica of such a mirror, we have fabricated a high quality matrix, namely, the glass lens with the following optical parameters: clear aperture diameter D=190mm, surface curvature radius R=400mm, the relative aperture of the mirror fabricated with this matrix being D/F=1/1.1. The working surface of the matrix showed high optical quality. This is illustrated in Fig.3. We carried out optical quality certification with interferometer of the firm Zyga at the wavelength of 0.6328µm.

As an elastic thin membrane, we used a 20 µm thick mylar film with aluminum coating. Transparency of this film at wavelength 0.63 µm amounted to 5%, and dispersion factor of the specular coating 10^{-2}.

3.3 Stages and peculiarities of fabrication.

I. At the first state of fabrication, we had to choose the film sample the most uniform in appearance, having no wrinkles, folds, splits since they just play the key role in formation of heterogeneities. This choice is conditioned by that we cannot get rid of existing in the film heterogeneities completely. We can only reduce them. However, this ultimately results in mirror's poor optical quality. Then first we straightened without straining the sample over the plane surface of a good quality glass plate being wetted by a liquid so that the film surface was plain. After this we glued to the film specially prepared for this technology ring having its working plane end accurately finished. Then we took off the ring with the film glued to it from the glass plate.

II. At the second stage we had to provide as uniform as possible strain within the limits of elastic deformations in the film while the material maintains its initial shape having been released of the strain forces. This strain is necessary to have plastic deformations over the whole mirror's clear aperture while forming the film on the matrix. We formed this strain in series with the use of the technological ring when fixing the film on the mirror 1 and then with the bearing ring 2 (see Fig.4). When fixing the film we specially attended to its fixation between press ring 6 and mirror 1 (see Fig.4) so that the film does not pull out from under the ring.

III. The third stage is the replica process. We applied the film prepared as required on the matrix where the film subjected to a certain force fitted the matrix and fixed in this state.

We had very carefully cleaned the surfaces of the film and matrix from dirt and dust in a specially appointed room before we contacted them. Otherwise presence of dust ultimately results in appearance of a lot of small hollows on the mirror's surface.

Without taking off the film from the matrix, we put the whole of construction into a heating and heated up to temperature150^0 ? , held it for a half hour, and then slowly cooled. Heat treatment

allowed us to 'freeze' the film's shape as well as to reduce not uniform stresses in the film. We chose this thermal regime due to the specific character of the considered task.

IV. The last stage consisted in taking off accurately the shaped film from the matrix. The result of all carried out stages was the mirror with its pre-shaped surface.

In spite of that the film's shape was 'frozen' it deformed while the film was taken off from the glass matrix. It caused by the fact that residual deformations kept in the film during the replica process. They gave the film stretched on the matrix not great additional strain. Therefore, the film shrank correspondingly when we took off the replica from the matrix. Thus, since the film by its properties is elastic and has negligible rigidity, the mirror formed though being 'frozen' changes its shape. It looked like that smooth bends (wrinkles) appeared on the formed surface.

To bring the mirror in its working state and restore the form close to the matrix one, it is necessary to repeat the forces applied to the film before taking off it from the matrix. We studied possibility of restoring these forces with the use of both gas pressure difference and electrical field.

We found out in our preliminary studies that maximum electrostatic force realized in the experiment was rather small that equivalent to the air pressure difference of $1.4*10^{-4}$atm. This relates with the breaking point of air disruption at electrical field intensity of about 3kV/mm. This force is insufficient to give the mirror its working shape (in space vacuum conditions this force might be several times greater). Therefore, we used in the mirror's construction along with electrostatic pressure a certain gas-pressure difference to model increase of the required force.

Thus, we brought the mirror in its working state in series. First, we formed a gas pressure difference to give the mirror some working shape. Then varying potential between the electrode and the membrane we could affect this working shape of the mirror. The electrode's configurations used can be different and have rather complex profile depending on that what forces we have to apply to the film to repeat the shape of the matrix.

Calculation of these forces is a very labour-intensive task. So, at the first stage of investigation of these mirrors, we confined ourselves to that we showed feasibility of electrostatic field effect on the mirror's surface shape with the use of a plane solid and segmented electrodes.

3.4 Description of model construction of pre-shaped membrane mirror.

Fig.4 shows a schematic of all units of the membrane mirror. Clear aperture diameter of the mirror amounts to 190mm.

The pre-shaped membrane 3 is fastened between the mirror's 1 body and press ring 6. Being just between these rings the membrane was stretched on the lens and was exposed to heating. When the membrane has acquired the required pre-shape these rings are not separated. The bearing ring 2 enables preliminary straining the film and at the same time forms the accurate surface supporting mirror's edge. To supply potential to electrode 4 is used waterproof connector 8. The electrode itself is close to the membrane and insulated from the device's body. Adjustment screws 9 serve for progressive moving and/or small inclination of electrode 4. In that way we could control the gap between the electrode and the membrane. To form the working shape of the mirror by means of a gas pressure difference we used the connecting pipe 5 for pumping out air. We provided for simple changing various electrodes of both plane and spherical shape.

This construction of the membrane mirror allowed us to meet the necessary requirements to such a mirror.
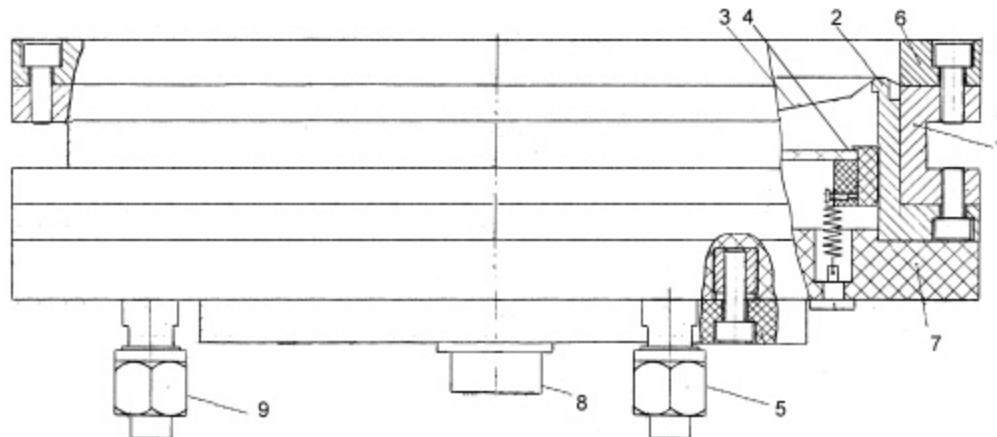

Fig.4. Construction of model of pre-shaped membrane mirror controlled by electrostatic field (1-body of the mirror, 2-bearing ring, 3-pre-shaped membrane,4-electrode, 5- connecting pipe for pumping out air, 6-press ring, 7- cover of the body, 8-electrical connector, 9-screw for adjustment of the electrode (three pieces)).

4. Examining optical quality of pre-shaped membrane -mirror model with electrostatic control.

Fig.5 shows the interferometer's scheme that we used for study of optical parameters of the mirror and feasibility of electrostatic control of its working-surface shape. The interferometer

consisted of beam splitting cube 3, high quality spherical reference mirror 5 (curvature radius 360mm, diameter 120mm), and membrane mirror 4 considered. To light the interferometer we used a point-like source produced by the focused by microscope 2 beam of He-Ne laser 1. We observed the interferogram on suffused screen 7 and registered the passed beam with digital camera 8. High quality objective 6 (focal length 250mm, diameter 100mm) built the image of mirror 4 on the screen 7. The interferometer was assembled on a vibro- isolated plate.
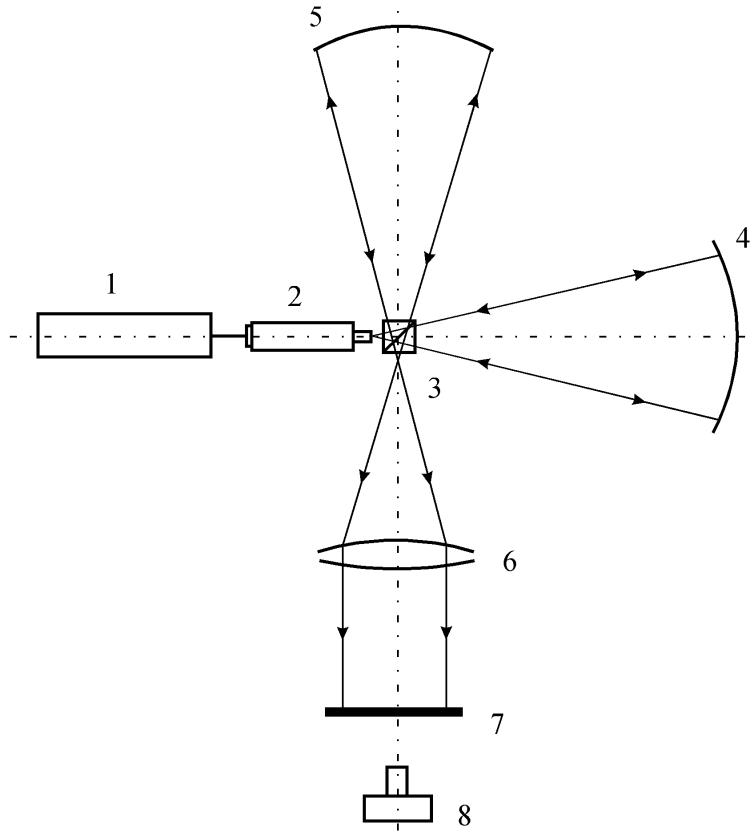
Fig.5 Optical schematic of interferometer. (1- He-Ne laser, 2- microscope, 3-beam-split cube, 4-membrane mirror, 5-reference spherical mirror, 6-objective, 7-screen, 8- CCD camera.)

It should be noted that we carried out the basic studies of this scheme of a membrane mirror within its central area 130mm in diameter, though diameter of mirror 4 was 190mm. This limitation caused by clear aperture size of the reference mirror. Fig.6 shows the typical interferogram of the membrane mirror with gas pressure inside its chamber that to provide its curvature radius equal to 400mm. Here the electrodes were not charge supplied.

The interferogram corresponds to tuning the interferometer with compensation for tilts and an average sphere in the central area of the mirror that is to tuning for the infinite width fringe in the central area.
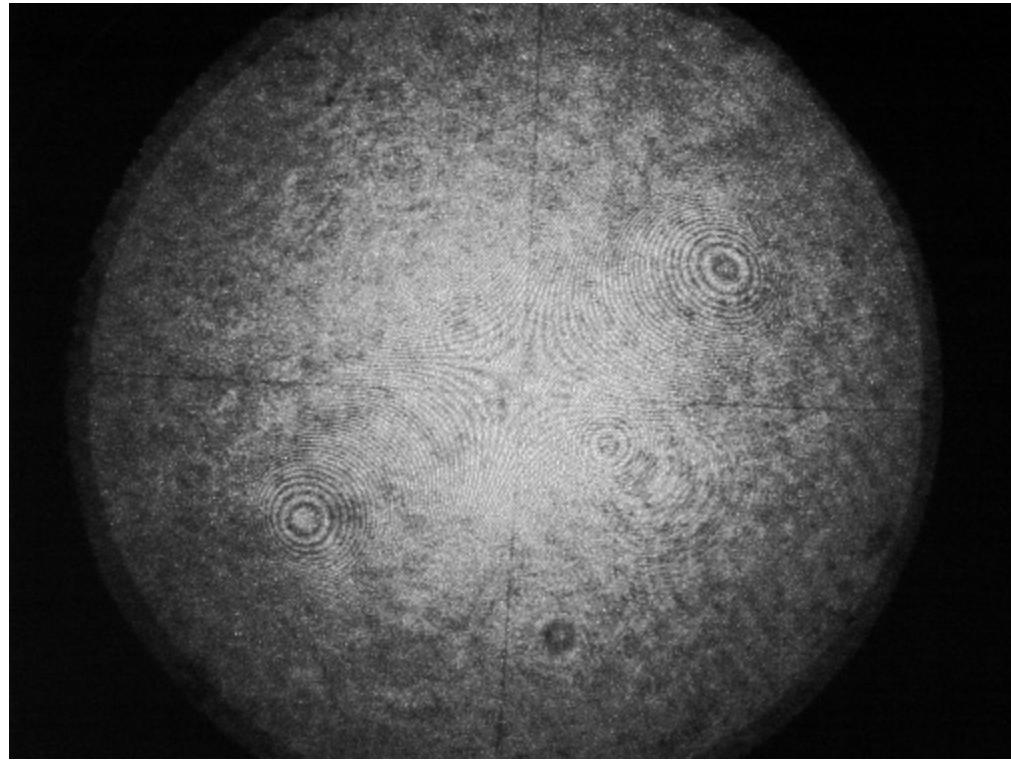

Fig.6. Interferogram of the membrane mirror without electrostatic control. The distance between two adjoining interference fringes corresponds to a local change of 0.315µm of the mirror's surface shape.

It is seen in the interferogram that the main deformation of the surface shape in its central area 50mm in diameter is astigmatism. The astigmatism primary sections are deflected clockwise by angle 45$^?$ from vertical and horizontal axes. The results of processing the interferogram have shown that the difference in mirror's curvature in the primary sections due to astigmatism amounts to about $\Delta?=1/R_m-1/R_s=0.026$ m^{-1}. For the average radius of the mirror R=400 mm the primary section radii equal R_m=397.8 mm and R_s=402.2 mm.

Let us consider mirror's quality over the entire interferogram in Fig.6. Along the meridional section there are two virtually equidistant from the center deformations of the 'local hole' type. They are seen in Fig.6 as the superposition of closed concentric interference fringes in the right upper and left lower quadrants.

Along the sagittal section the sprip period is getting progressively smaller with increasing distance from the center. The fringes become indistinguishable at a distance longer than 30mm. These data prove to presence of a spherical aberration in the mirror together with astigmatism. This aberration in a near-axis area (D<50 mm) is essentially smaller than astigmatism and virtually does not distort the typical for astigmatism interferogram appearance.

However, as one moves away from the axis the spherical-aberration contribution leads to drastic alterations in the interferogram. In the sagittal section, astigmatism and the spherical aberration coinciding in sign sum up their effects so that the interference fringes become indistinguishable already at small distances from the axis. In the meridional section, these aberrations are different in sign (within the area in Fig.6) and partly compensate for the effects of each other (subtraction). Presence of distortions of the 'local hole' type in the meridional section is also the result of a combination of astigmatism and spherical aberrations.

Thus, the considered model of the pre-shaped membrane mirror with electrostatic control had within the central area 130 mm in diameter the deformations of its shape of the type of astigmatism and a spherical aberration.

Presence of astigmatism was due to imperfection of the mylar film used for the mirror. The film was prepared by a flatting method and thus had anisotropy of its mechanical features along the both flatting and perpendicular directions.

With the described above method of mirror's fabrication including a number of heat treatment stages aimed at reducing of inner heterogeneities in the film, we could essentially decrease the astigmatism aberration of the mirror. However, we could not avoid astigmatism completely with this film at the stage of fabricating the mirror. Residual astigmatism in relative measure amounts to only $(R_m-R_s)/R=1.1\%$. It can be compensated by methods of non-linear optical correction.

Presence of the spherical aberration of the pre-shaped mirror is caused by physical principles of building the membrane mirrors, the laws of strain and bend of thin membranes subjected to the forces produced by mechanical stretching and a gas pressure difference. One can perhaps reduce this aberration studying in detail the process of forming the thin membranes, optimizing formation-process parameters, and primarily using non-spherical lenses as the forming matrix, and also developing methods of local effects for shaping the membrane etc.

5. Feasibility study of electrostatic control of membrane-mirror working surface.

In the framework of this project, we carried out the feasibility study of controlling the working surface of membrane mirrors with electrostatic attraction of the membrane to an electrode. The advantages of this method are well known.
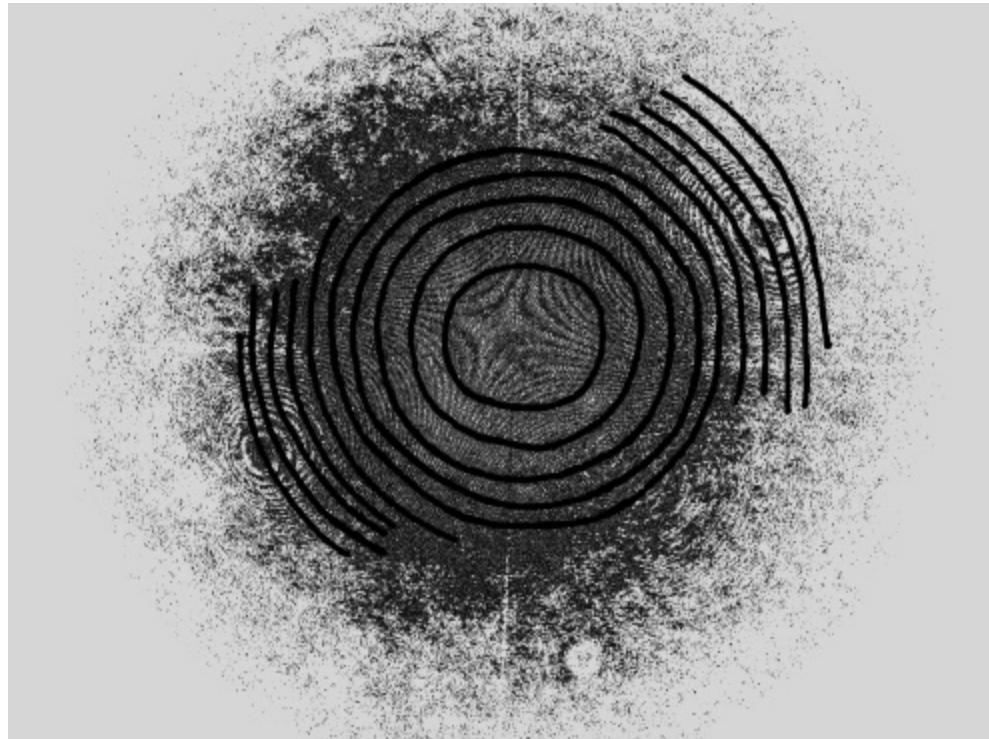

Fig.7   Interferogram of wave-front subtraction obtained by double exposure method (For clearness the moiré fringes are marked out. The distance between two adjoining fringes corresponds to the change 0.315µm of mirror's surface shape due electrostatic forces)

First of all, it is possibility to avoid excess gas pressure and a transparent cowl in space conditions. Besides there opens some feasibility of a local effect on the membrane using profiled or segmented electrodes as well as different over a mirror's section controlling voltages.

We studied feasibility of electrostatic control at the membrane-mirror model with the use of the interferometer described above. During this study, we registered two imterferograms of the mirror: one for the case of the charged electrode, and the second for the ground connected electrode. While registering the interferograms, we did not change mirror's parameters (initial strain of the membrane, air pressure in the mirror's chamber etc.

We estimated the degree of electrostatic attraction effect on the mirror's surface shape via the difference of wave fronts registered in the intrferograms. We carried out processing data obtained by the traditional method of restoration of the wave fronts with the interferogram and further subtraction of them as well as by the widely used in holography the interferometry method of double exposure. In the last case, we could see the interferograms coinciding to a great accuracy and we observed the moiré picture as the interferogram of signal subtraction. Note that the both methods of data processing resulted in virtually the same results. Below we present the main results of the study in the form of moiré pictures as the most obvious.

Fig.7 presents the interferogram of wave-front subtraction corresponding to the effect of electrostatic attraction of the membrane to a plane solid electrode.

These results are for the case of the distance between the membrane mirror vertex and the electrode equal to 2mm and voltage 3kV. As is seen in Fig.7 the subtraction interferogram is a superposition of concentric round rings typical for a defocusing aberration. It is also seen that within the 100mm size area the flexure due to an additional curvature induced by electrostatic forces amounts to about 3.3µm.

This additional curvature corresponds to changing mirror's radius from R=400 mm to R= 399.6 mm. Note that maximum intensity of electrical field in this experiments amounted to 1,5 kV/mm that was half as large as the limit intensity of electric field resulting in disruption of dry dust-free air at atmosphere pressure. We did not aim to increase the field intensity so that not to damage the membrane by casual disruption. Note that in space conditions one can realize essentially larger intensities than those used in our experimental demonstrations.
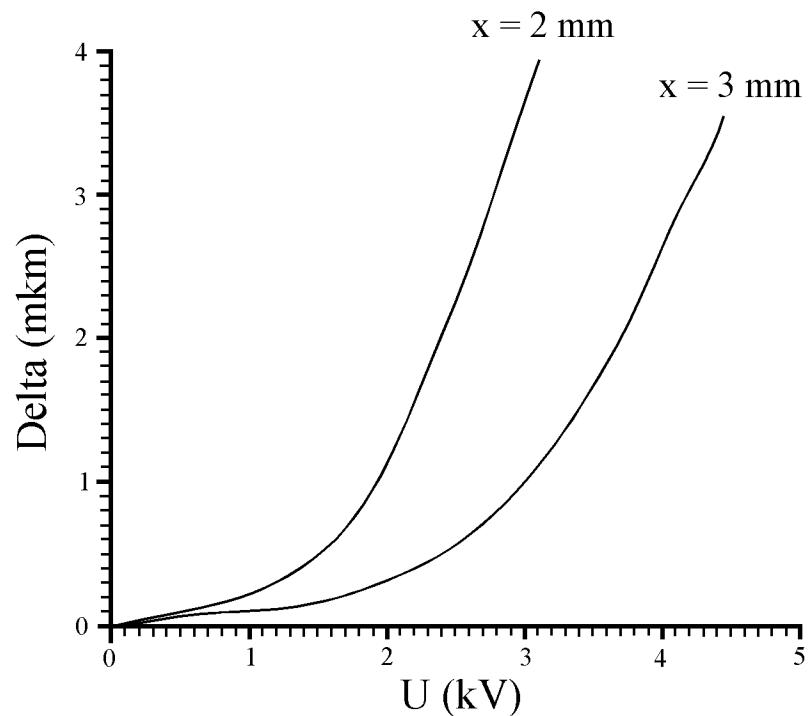
Fig.8. Flexure of sphere Delta induced by electrostatic forces as function of voltage U at different membrane-electrode distances X.
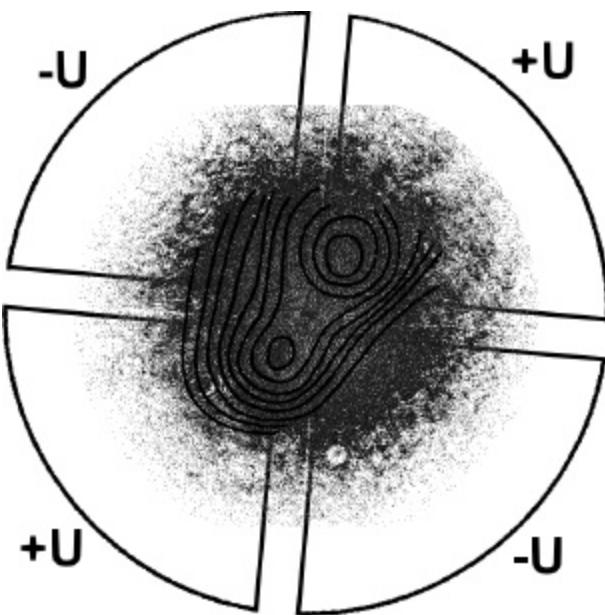

Fig.9   Interferogram of subtraction of wave fronts obtained by double exposure technique and configuration of electrode sections. For clearness the moiré fringes are marked out. The distance between two adjoining fringes corresponds to the change 0.315µm of mirror's surface shape due electrostatic forces.
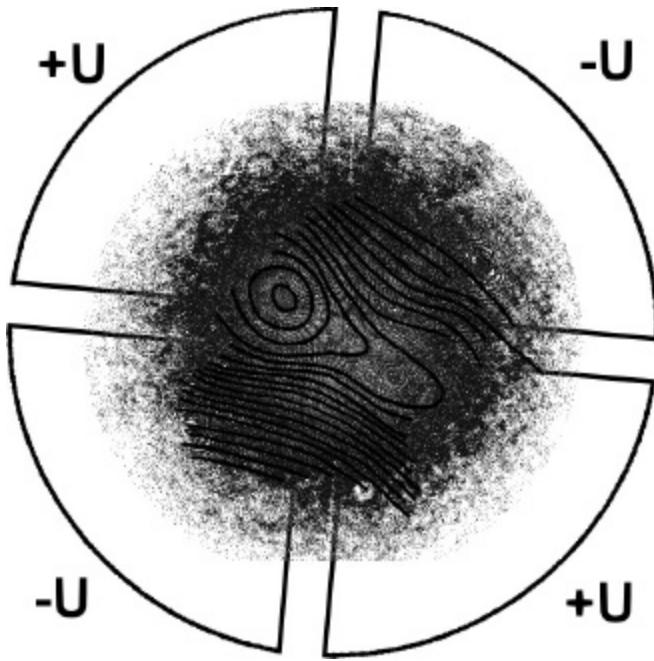
Fig.10. Interferogram, similar brought on Fig.9, tinned under opposite polarities of connecting the electrodes.

Fig.8 shows the flexure of an additional electrically induced sphere as function of the voltage for different distances between the membrane and the electrode. The data are limited in field intensity by air disruption that was observed at about 1.5 kV/mm. Disruption at this intensity was apparently caused by field irregularity due to a spherical shape of the film, imperfectness of the electrode, residual dust in the mirror's chamber etc. It is seen in Fig.8 that the mentioned functions are appreciably non-linear. Thus, an effect on the film appears to be rather weak at intensity less than 1?V/mm. At the intensity ranged from 1?V/mm to the intensity of disruption the effect on the film is fast getting greater, the function being close to linear.

The results in Fig.8 show that electrostatic forces can be several times greater at a larger intensity of disruption (for example, up to 30 kV/mm in space conditions).

The above results were obtained with the solid plane electrode. The nature of electrostatic effect on the membrane (in the considered near-axis area 130mm in diameter) is close to that of air pressure difference in the mirror's chamber. In the both cases, we observe changing the total curvature of mirror's surface.

To study the feasibility of local affecting the membrane we have fabricated a number of segmented both plane and profiled electrodes. Fig.9 and Fig.10 show interferograms obtained in the experiments with the plane electrode in the form of 4 isolated one from another segments of total diameter of 170mm. Figures show also an electrode configuration and voltage polarity at each

segment. The mirror's body and the film were connected with the power supply minus. We carefully finished the electrode, rounded off sharp corners of the segments.

The distance between the film and the electrode along the axis was 2mm, voltage 4.4kV. Polarity of the voltage applied in couple to opposite electrodes was different in Fig.9 and Fig.10. In these figures the subtraction interferogram (moiré fringes) corresponds in the first approximation to the distortion of the type of an 'extended sphere' or to a superposition of a cylinder and a sphere, extension being asymmetric. The depth of the induced distortion of the mirror' surface (within the considered area 130mm in diameter) is equal to 2.4µm that is 2.5 times less that one could expect in the same conditions for the solid electrode (see Fig.8).

There are also distortions of the type of 'local hole' seen in Fig.9 and Fig.10 in the form of a superposition of closed concentric moiré fringes near the corner of every electrode with the positive polarity. The seen direction of the distortion (direction of extension of the sphere) is close to the bisectors of the segments having positive polarity and thus attracting the membrane.

It follows from the interferograms in Fig.9 and Fig.10 that in compliance with changing polarity the character of the electrostatic effect changes too. These data obviously show feasibility of local affecting the membrane-mirror's shape with the use of forces of electrostatic attraction.

6. Conclusions.

1) We have realized the pre-shaped membrane mirror of diameter D = 190mm and curvature radius R = 400??. F-number of this mirror is R/2D=1.05.

2) We have obtained the interferogram of the working surface of the pre-shaped membrane mirror. It follows from the experience of this work that it is possible to correct aberrations of such a mirror by non-linear optical methods.

3) The basic optical distortions of the realized mirror are a spherical and a cylindrical aberration. To eliminate a spherical aberration one has to use non-spherical matrices when forming a pre-shape for the membrane. To reduce a cylindrical aberration it is required to use membranes with isotropic in all directions mechanical features.

4) One can change the total curvature of the mirror applying additional uniform electrostatic attraction to the membrane. We used in our experiments not great in magnitude electrostatic force taking into account the air disruption factor in our conditions. In vacuum one can realize greater electrostatic forces.

5) Employment of the simplest segmented electrode (of four quadrants) allowed us to demonstrate controlling the shape of mirror's surface. In particular, we have shown feasibility of compensation for cylindrical aberration by electrostatic forces.